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Energy and Chemicals from Native Grasses: Production, Transportation and Processing Technologies Considered in the Northern Great Plains

by

Douglas G. Tiffany, Brendan Jordan, Erin Dietrich and Becca Vargo-Daggett

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This research was funded by Initiative for Renewable Energy and the Environment, Great Plains Institute for Sustainable Development, and the Minnesota Agricultural Experiment Station.

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This project was sponsored and funded by the Initiative for Renewable Energy and the Environment and the Great Plains Institute with Steven J. Taff generously serving as Principal Investigator. The project grew out of the desire to summarize and integrate selected papers by three students from the Humphrey Institute who completed papers as requirements for a course entitled “Energy from Grass,” which was taught by Vernon Ruttan and Douglas Tiffany. That class was funded by the Great Plains Institute (GPI) based in Minneapolis, MN, through a U.S. Department of Energy grant that had been awarded to that organization to administer. There are many others who contributed to this project substantially, but who are not authors.

The GPI sought to investigate the prospects of utilizing native prairie grasses in a novel way to produce valuable chemicals and energy in the Great Plains Region. The board of GPI under the leadership of Sara Bergan, director, assembled research participants from academic institutions and business. The concept was to grow native prairie grasses with known environmental benefits and process that grass into valuable chemicals and energy by use of pyrolysis, which consists of rapidly heating finely ground biomass in the absence of oxygen and then quenching the volatile fractions of biomass as liquids.

Arvid Boe, Vance Owens, and DoKyoung Lee, from South Dakota State University conducted research regarding production levels and techniques and the amounts of carbon that native prairie and Switchgrass stands would be capable of sequestering. Ken Higgins from the United States Geological Survey conducted research on the relationship between avian density and grass diversity on harvested native grass plots.

Ensyn, Ltd., company that has developed and utilized pyrolysis equipment and processes, was also a participant. David Boulard and Barry Freel, in particular, represented Ensyn on this project due to their expertise and the development work done on pyrolysis by that company. Ensyn has for some years participated in a joint venture with Red Arrow, Inc. to produce liquid smoke flavoring for food products derived from bio-oil produced at several locations in Wisconsin using wood. Ensyn performed pyrolysis processing on native grass samples for this project.

Ted Aulich, Edwin Olson, and Chris Zygarlicke of the Energy and Environment Research Center (EERC), located at the University of North Dakota in Grand Forks took on the role of chemically characterizing the bio-oil derived from native prairie grasses. EERC has patented a process using a solid acid catalyst, which can hydrolyze molecules of anhydroglucose (AHG) formed during the pyrolysis reaction into anhydrosugars (AHS). The plan then was to ferment the resulting six-carbon AHS and produce ethanol. In addition to AHG, native prairie grasses were expected to produce significant amounts of hydroxyacetaldehyde (HA), which could serve as the base for production of various organic compounds such as adhesives.

Marc Von Keitz of the Biological Process Technology Institute at the University of Minnesota performed fermentation trials with the sugars (AHS) yielded from the anhydroglucose (AHG) fraction of bio-oil derived from both prairie grasses and wood.

As mentioned above, Doug Tiffany and Vern Ruttan taught a semester-long capstone class to Masters students in the Humphrey Institute of Public Affairs with sponsorship by the GPI. During the class, the students were guided to research topics relevant to the overall mission of evaluating the economic and policy dimensions of the prospects for using pyrolysis to produce chemicals and energy from native prairie grasses. In this regard, Becca Daggett researched production economics of native prairie grass, Brendan Jordan investigated and modeled the transportation costs of moving native prairie grass to a processing site, and Erin Dietrich reviewed prevailing and potential farm policy and the Conservation Reserve Program (CRP) in order to gauge the locations of significant native prairie stands and opportunities to use those stands in the framework of existing programs. A fourth student, Adeel Ahmed, wrote a fine paper that identified government subsidies for existing energy supplies, both fossil and renewable. However, his work doesn’t logically fit into the framework of this paper, which is more directed toward production economics.

As authors we are grateful to the Initiative for Renewable Energy and the Environment for funding the efforts of Doug Tiffany and Brendan Jordan to condense and integrate research for the Great Plains Institute-funded class as well as the additional research completed by those two authors.

Abstract:

Production of biomass from native prairie species offers the opportunity to produce energy and chemicals while providing substantial ecological services in the Northern Great Plains. This paper analyzes the application of rapid pyrolysis to produce bio-oil, which has the potential for use as a low-grade fuel oil or as a source for extraction of valuable chemicals. Yields of bio-oil, the quantities of extractable chemicals, and chemical prices drive the economics of this concept, which has a more extensive track record utilizing wood chips. A spreadsheet model was developed to determine gross margins available to defray costs to extract and refine such chemical products as hydroxyacetaldehyde, phenol, formic acid, acetic acid and various resins. Although efforts to hydrolyze anhydroglucose were successful, efforts to produce ethanol from the resulting six-carbon sugars were unsuccessful in a related trial. To understand the overall project economics, it was necessary to consider the availability and productivity of lands in the Northern Great Plains that can provide low cost native prairie grasses including Big Bluestem and Switchgrass. Production economics and transportation economics were analyzed to determine the costs of native prairie grasses delivered to a plant capable of pyrolyzing the biomass. Competing technologies that could also use native prairie grasses are considered as well as policy alternatives important for production of energy and chemicals from native prairie grasses.

Key words: prairie grasses, pyrolysis, economics, chemicals, energy, bio-oil

Executive Summary

This project investigates aspects of economic and technical feasibility of harvesting native prairie grasses in order to produce chemicals and energy in the Northern Great Plains. Because native prairie grasses were the primary climax vegetation in this region, there are expectations of enhanced carbon sequestration, water quality improvements and wildlife enhancement by the inclusion of greater proportions of native prairie grasses on landscapes in this region versus contemporary crops and forages that require frequent and energy intensive disturbance of the soil.

Land recruitment from existing federal farm programs as well as the rates at which Conservation Reserve Program (CRP) contracts will expire in the states of Minnesota, North Dakota, and South Dakota are analyzed. It is clear that the production of native prairie grasses on CRP acres results in cheaper biomass on a per ton basis. Numerous areas of these three states could support businesses that process native prairie grass.

Production economics involving establishment and maintenance of forage stands that include native species were developed to determine geographic regions and yields of native grasses that result in low cost biomass. Various harvest regimes are considered. Various sources suggest that harvest of CRP acres can be permitted with beneficial effects on the native prairie stands while being consistent with environmental goals of CRP.

Transportation economics are often pivotal in the success of biomass projects, so modeling was carried out to determine average transportation costs per ton within various prescribed production radii of an assumed processing center. In addition marginal transportation costs per ton of expanding the transportation radius an additional mile were calculated in order to assess the savings of a more constricted biomass shed. In the cases modeled, the density of native prairie grass plots on CRP did not pose major problems in securing adequate supplies to feed a processing plant of defined scale.

The scientific and industrial communities have far more experience and success pyrolyzing wood into bio-oil than native prairie grasses. Potassium levels are higher in herbaceous plants than in woody plants, and that element serves as a catalyst to chemical reactions that reduce yields of hydroxyacetaldehyde (HA) and anhydroglucose (AHG), the two most valuable groups of chemicals formed by pyrolysis. Success was achieved by the EERC staff in utilizing their patented process to hydrolyze AHG into six-carbon sugars; however, these sugars proved recalcitrant when exposed to various fermentation organisms, resulting in minimal yields of ethanol. At this time further improvements in removal of toxic agents from the AHG fraction must be achieved before it is feasible to ferment the sugars hydrolyzed from the AHG's yielded by pyrolysis of native prairie grasses. This technical finding has strong economic implications by reducing the value of the chemical products that can be derived from bio-oil. On an optimistic note, glucose

hydrolyzed from AHG fractions derived from pyrolysis of wood proved to be more easily fermentable. Perhaps further research efforts will uncover key differences in the bio-oil derived from wood and grasses.

The authors offer discussion of alternative uses of bio-oil aside from derivation of chemicals and energy, such as its potential use as a substitute for distillate oil in boilers or its use in combustion turbines to produce electricity. At this time of crude oil costing more than $60 per barrel, bio-oil derived from biomass appears to be competitive on a cost per BTU basis as a low-grade fuel oil For bio-oil to be used successfully, it is evident that further refinement and the use of additives will be necessary The authors identify further research that will be needed in order to utilize bio-oil derived from native prairie grasses grown on the Northern Great Plains. In addition, other techniques of utilizing native prairie grasses that may compete with pyrolysis are discussed.

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Introduction

This paper provides a system-wide concept analysis of using native grasses grown on Conservation Reserve Program land in the northern Great Plains as an energy fuel. The Great Plains has been identified as an ideal region for producing native grass biomass for the following reasons:

- Interest among farmers in finding alternative crops to complement or substitute for conventional crops that are often less successful in dry conditions, short growing seasons and marginal soils of the region;
- the abundance of land enrolled in the Conservation Reserve Program, which could serve as a base of native grass energy crops and;
- the comparative advantage of growing grasses in the Great Plains due to low land rental rates.

This paper attempts to answer a series of questions regarding the feasibility of a yrolysis-based biorefinery project using native grass feedstocks from CRP land in the Northern Great Plains. Some questions addressed are the following:

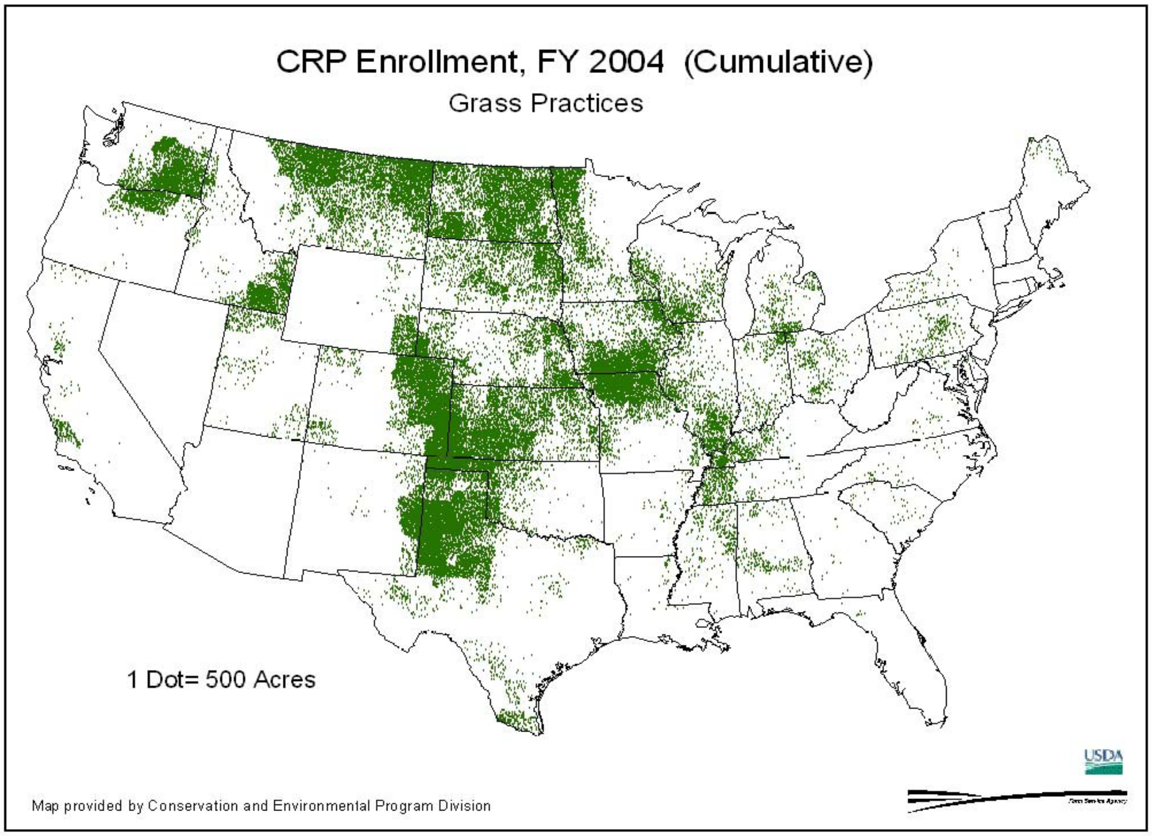
1) Can native grasses be harvested from CRP land in a way that is consistent with the environmental benefits of the program, including carbon sequestration, creating habitat for wildlife, maintaining diverse mixtures of native perennial grasses on the landscape, improving water quality and decreasing soil erosion?
2) Is there a sufficient land-base enrolled in CRP in the Northern Great Plains to produce adequate feedstock for a reasonable sized pyrolysis plant?
3) What will it cost to produce, transport and store native grass biomass in the region?
4) What is the feasibility of producing bio-oil from biomass through pyrolysis?
5) What is the overall feasibility of the project?
6) What are other uses of native prairie grasses?

The Conservation Reserve Program

The Conservation Reserve Program was first introduced in the Food Security Act of 1985 to encourage farmers to set aside marginal tillable land in order to decrease soil erosion and reduce surplus agricultural production. The program evolved over the years to provide greater habitat and conservation benefits through the development of the Environmental Benefits Index (EBI) used to rank lands offered into the program and to encourage favorable practices on those lands. The program is popular among farmers, as well as conservation groups and hunters groups, the latter two groups reporting increased wildlife on CRP land.

As the national map of CRP grassland enrollment demonstrates in **Figure 1**, there are areas of very high enrollment, both in total acreage and density of acreage, at the border of Eastern Washington and Eastern Oregon, in Northern Texas, at the border of Colorado, Kansas, and the Oklahoma panhandle, at the border of southern Iowa and northern Missouri, and a large area encompassing eastern Montana, northern South Dakota, western Minnesota and much of North Dakota.[1] This study focuses on CRP acreage in eastern North Dakota, north eastern South Dakota, and western Minnesota. CRP enrollment is high in all three states, as demonstrated by **Table 1**.

Figure 1.



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[1] USDA - FSA 2006

Table 1. Total cropland acreage and total active acreage enrolled in the Conservation Reserve Program in Minnesota, North Dakota and South Dakota

	Total Cropland acres in 2002 (USDA-ERS 2006	Active CRP Acres in April 2006(USDA-FSA 2006)
Minnesota	22,730,000	1,793,627
North Dakota	26,510,000	3,365,674
South Dakota	20,320,000	1,506,369

There is precedent for harvesting CRP land. The 1995 Farm Bill includes provisions allowing certain economic uses of CRP land, which were clarified in the 2000 Farm Bill to include up to 6 biomass energy projects nationwide, and no more than one per state. These provisions allow harvesting of biomass on CRP land for energy production (FSA 2000). Although some CRP land is specifically excluded, energy production is permissible on most CRP practices. The following criteria must be met:

- Acreage may not be harvested more than once every other year
- No more than 25% of the total CRP acreage in any NASS Crop Reporting District may be harvested in any one year
- No commercial use may be made other than energy production from biomass
- The total of all projects may not exceed 250,000 acres and individual pilot projects will not generally be approved if they exceed 50,000 acres.
- A payment reduction equal to 25% of the annual rental payment will apply during the year the acreage is harvested
- Harvesting must be completed between September 1 and September 30 (although the Chariton Valley harvests later)
- Pilot projects must be conducted for a minimum of 10 years

The USDA selected six pilot projects, all of which involve co-firing biomass from CRP land with coal in a combustion application to produce electricity. Four of the projects, in Iowa, Illinois, Oklahoma, and Pennsylvania, involve native grasses (typically Switchgrass). Two tree biomass projects were also selected. Minnesota’s project will use hybrid poplar, and New York’s will use willow (FSA 2002).

Iowa’s project, the Chariton Valley Biomass Project, is the most advanced of the CRP bioenergy pilot projects. Chariton Valley took advantage of this pilot program to develop a feedstock supply of Switchgrass grown on CRP land to supplement the coal supply to Alliant Energy’s Ottumwa plant in southern Iowa. The goal of the project was to eventually provide 35MW of biomass electricity from 200,000 dry tons of Switchgrass grown on 50,000 acres of land.

The third provision, banning the use of CRP biomass for anything other than energy production, appears to preclude selling components of bio-oil such as high-value chemicals. This rule would have to be modified to allow this practice, or the project would have to depend on grass production from non-CRP land, or the CRP biomass project would have to exclusively produce energy and not other products such as chemicals. The 50,000 acre limitation described above would still be ample acreage to support a demonstration scale project. Assuming yields of 3 tons per acre, and hence 150,000 tons of biomass, a 50,000 acre biomass project could support a 400 ton per day pyrolysis plant (discussed in more detail later). This is larger than any existing commercial pyrolysis facility, and is the largest theoretical pyrolysis plant generally discussed in academic and industry literature.

Environmental Impacts and Feasibility of Harvesting CRP

Several of the rules imposed for harvesting CRP for the biomass pilot projects were intended to preserve the environmental benefits of CRP. In particular, rules limiting harvesting to every other year, and limiting harvest times to the month of September are both intended to preserve the wildlife benefits of the land. Annual harvesting could reduce bird habitat and possibly reduce the survival of the stand of native grasses. Harvesting in the fall does not interfere with summer nesting birds. Since the CRP harvest is limited in scope and size, serious impacts on the conservation benefits are unlikely. If biomass programs were to be expanded, it is important to determine how the environmental benefits of CRP can be maintained under a larger-scale biomass production regime. Perhaps the inclusion of “islands” of unharvested refuges over the winter or areas of at least six inch high stubble may be helpful in providing nesting cover for certain bird species the following spring and winter cover. Energy production may actually improve the conservation value of CRP land by encouraging more active management, which would prevent the introduction and spread of non-native cool-season grasses such as smooth brome grass. At least one federally endangered species of orchid, the Western Prairie Fringed Orchid, may be compatible with haying (Fuller 2004, Gilley et al 2000).

CRP has been demonstrated to provide a host of environmental benefits, including:

1. Prevention of soil erosion and improving surface water quality by reducing run-off
2. Reduction of pollution by the application of lower chemical inputs on CRP versus conventional crops;
3. Increase of soil carbon; and
4. Creation of wildlife habitat.

Finally, planting of millions of acres of native grasses could be considered an inherent environmental benefit from the perspective of biodiversity, particularly if multi-species plots are planted and maintained.

The environmental benefits of CRP derive primarily from the deep root systems of the grasses. The roots stabilize the soil and prevent soil erosion. Plants sequester carbon to build roots, and much of this carbon remains in the soil for long periods of time – which both promotes healthier soil and helps mitigate the most important greenhouse gas. Because so many environmental benefits derive from the health of the stand of grasses and their root systems, a major question regarding harvesting is whether or not harvesting harms the stand.

Though most academic emphasis has been on Switchgrass, there may be advantages to planting multi-species crops that combine Switchgrass with other native grasses such as Big Bluestem, Little Bluestem, and Indian Grass. It makes intuitive sense that a diverse stand should have better odds of survival over a period of many years than a monoculture of Switchgrass, with diverse species able to exploit available growing conditions at different times and conditions.

An additional rationale for focusing on grass mixtures is that the CRP program currently provides incentives for them. Many participants in CRP have, over the years, switched to mixtures of native prairie perennials, rather than monoculture grasses. Since this is likely to continue to be a program requirement, it is important to evaluate the potential to produce high yields of biomass using perennial mixtures. Appearing below are the seven national ranking factors in the EBI scoring system are used to help local Farm Service Agency offices score and select acres offered for CRP:

- wildlife habitat
- water quality
- on-farm reduced erosion
- enduring benefits
- air quality
- conservation priority areas
- cost

Up to 100 points can be earned in the “wildlife habitat” category. Of those, up to 50 points can be earned merely by having up to 5 different species. Further points come from having native or endangered species.

There is considerable evidence in the academic literature that diversity in grassland species is correlated with high above ground (and below ground) biomass. (Tilman et al 2001) describes a 7-year experiment where randomized combinations of 18 grassland perennials were studied in 168 experimental plots. The study found that any combination of 16 species had 2.7 to 2.9 times more aboveground and total biomass than the average of all monocultures studied. Many of the mixtures had higher total biomass than even the highest yielding monocultures. This research provided a rationale for broadening South Dakota State University's research on both native grass monocultures and grass mixtures to study the characteristics of native grasses for energy crops. Some findings on grass mixtures include the following:

- In plots where a mixture of Switchgrass, Big Bluestem, and Indian grass are planted, Switchgrass is the dominant species in the establishment year and the 1st year after establishment. Big Bluestem is the dominant species in the second year after establishment.
- Switchgrass monocultures produce the greatest amount of biomass.
  Cellulose and hemicellulose do not differ significantly between grass species.
- Although grass mixtures with smaller numbers of total species (in this case 3) seem to decrease yields over a monoculture of Switchgrass, it is still possible to achieve yields from 3-10 Mg ha^{-1} (1.5-5 tons per acre).

Using grass mixtures rather than monocultures has other benefits that compensate for lower yields. Native prairie grass mixtures may continue to be a requirement of the CRP program, making them a precondition for using CRP as a biomass program. Furthermore, diversity of grassland species is correlated with higher avian density, implying that native prairie mixtures are consistent with enhancing bird populations.

Diversity may also reduce soil erosion. Switchgrass, as a monoculture, grows in clumps separated by bare soil. When Big Bluestem is added to a plot, it fills in the areas around the Switchgrass. This would be expected to further stabilize the soil.

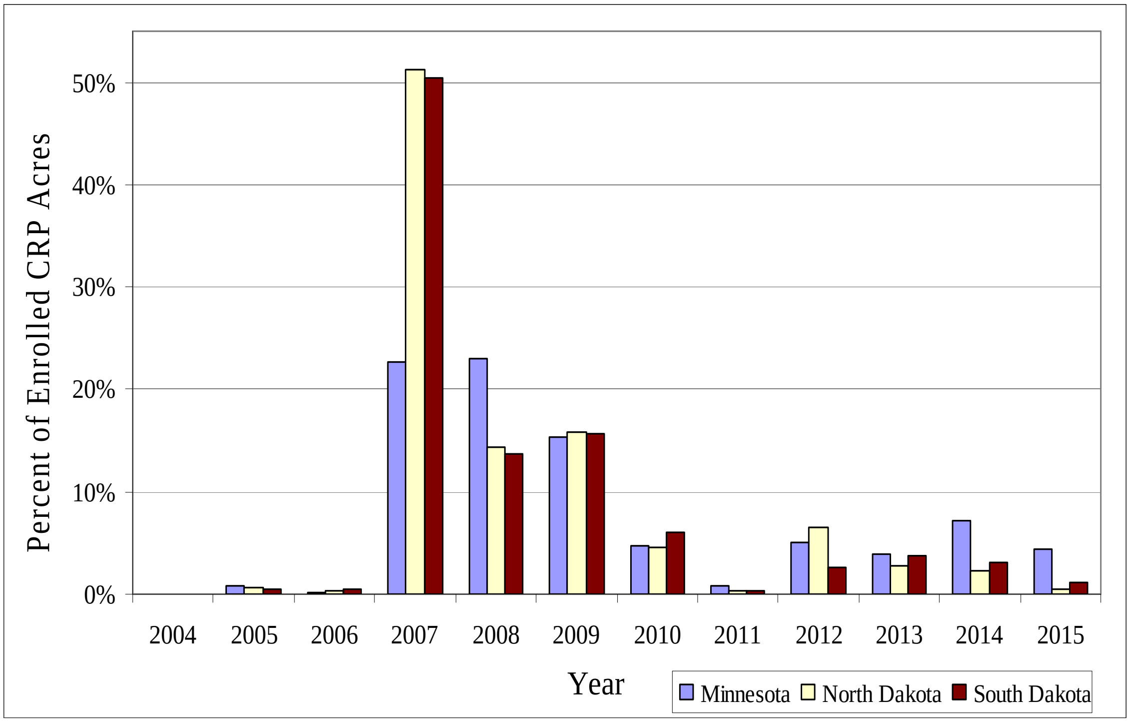
Researchers at SDSU also sought to determine whether CRP could be harvested without negatively impacting the health of the stand (and therefore the environmental services it provides). Initial conclusions are that CRP can be harvested, but should not be harvested more than every other year.

Researchers tested soil carbon as a result of harvesting. Although only 3 years of data have been collected, initial results suggest that harvesting may actually increase carbon sequestration. This is consistent with other studies. This is an important finding with regard to the possible impact of agricultural land use on climate change. There is a general understanding that when land is placed in native grass cover after being used for annual crops, there is an immediate positive impact on carbon sequestration. This effect continues for a series of years, but eventually diminishes. The CRP plots examined in this particular study were old, and would likely have slowed in their rate of carbon sequestration. If harvesting could increase carbon sequestration again, then harvested prairie species on land in perennial cover could be an ongoing resource for climate mitigation and also perhaps on-going revenue from carbon permit sales in a carbon-constrained world.

Expiration of CRP Acres

Review of the number of CRP contracts in the states of Minnesota, North Dakota, and South Dakota reveals the timing when a great deal of land may return to crop production or else a successor program to the CRP. Formulation of policies to manage re-enrolled CRP acres is a timely issue, indeed. **Figure 2** dramatically shows the magnitude of lands that previously qualified for the CRP whose owners may be interested in a modified CRP program that would permit some level of harvest in 2007-2009. As the figure demonstrates, around 85% of acreage in the region will expire between 2007 and 2010.

Figure 2: Retiring CRP acreage per year as a percentage of total acreage for Minnesota, North Dakota, and South Dakota.



Native Prairie Grass Production Economics

Switchgrass was selected in 1991 by the Bioenergy Feedstock Development Program at Oak Ridge National Laboratory as an ideal biomass energy crop after screening over 30 herbaceaous crop species during the 1980s. Switchgrass is a native grass, ranging from Quebec in the north to Central America in the south. It thrives under a variety of conditions, ranging from arid shortgrass prairie to brackish marshes and forests. Switchgrass is a C4 plant, which refers to the fact that the first stable product of its photosynthesis is a four carbon carbohydrate. C4 plants are very efficient in terms of yields of photosynthesis. In addition Switchgrass also has very high water use efficiency and thrives under drought conditions.

Switchgrass is a perennial grass that concentrates most of its growth into a deep and dense root system. This has benefits both in promoting soil stability and in sequestering carbon in the root system. Once established, a Switchgrass stand can persist for many years under the right conditions (possibly indefinitely), which leads to low maintenance costs relative to conventional row crops that require tillage and must be replanted every year.

The production economics of native grasses, assuming likely yields for Switchgrass or high-yielding grass mixtures, were studied. Total production costs were evaluated for three counties that were considered ideal for biomass production due to high concentrations of CRP land, low land rents, and somewhat erratic performance of conventional agriculture. One county was selected for detailed analysis in each of three states: Lincoln County in Minnesota, Eddy County in North Dakota, and Marshall County in South Dakota. Realistic assumptions were made about likely grass yields in those areas. A review of other studies analyzing native prairie grass production is found in **Appendix A**.

The cost per ton of biomass is determined by land rents, harvest schedules, native grass yields, and CRP payment levels. **Table 2** shows the break-even price per ton a farmer would need to be paid to equal the costs of production, including establishment costs amortized over 20 years, annual operating costs, harvest costs, and land rental payments under different harvest schedules: annual, biennial, and triennial harvests. Detailed assumptions of the farm budgets are found in **Appendix B**. Which harvest scenario is the best is unclear. The CRP program currently allows only biennial hay harvest. Annual harvesting on all land is not permitted nor may be desirable from the standpoint of soil conservation and wildlife cover. As **Table 2** illustrates, however, cost per ton is less for more frequent, annual harvests.

Table 2. Costs per ton of biomass grown (including land rent and production costs) varied by harvest schedule and CRP payment.[2]

	Lincoln county			Marshall County			Eddy County		
Scenario	harvest and collection cost per ton	production cost per ton	total cost per ton	harvest and collection cost per ton	production cost per ton	total cost per ton	harvest and collection cost per ton	production cost per ton	total cost per ton
Annual harvest, full CRP	$ 17.66	$ 4.90	$ 22.56	$ 18.32	$ 5.60	$ 23.92	$ 19.43	$ 5.00	$ 24.43
Biennial harvest, full CRP	$ 17.66	$ 5.00	$ 27.45	$ 18.32	$ 9.79	$ 29.52	$ 19.43	$ 11.20	$ 29.43
Annual harvest, reduced CRP in harvest years	$ 17.66	$ 8.13	$ 25.79	$ 18.32	$ 8.62	$ 26.94	$ 19.43	$ 7.77	$ 27.20
Biennial harvest, reduced CRP in harvest years	$ 17.66	$ 13.03	$ 30.69	$ 18.32	$ 14.22	$ 32.54	$ 19.43	$ 12.77	$ 32.20
Annual harvest, no CRP in harvest years	$ 17.66	$ 17.83	$ 35.49	$ 18.32	$ 17.67	$ 35.99	$ 19.43	$ 16.09	$ 35.52
Biennial harvest, no CRP in harvest years	$ 17.66	$ 22.73	$ 40.39	$ 18.32	$ 23.27	$ 41.59	$ 19.43	$ 21.09	$ 40.52
Biennial harvest, no CRP	$ 17.66	$ 35.67	$ 53.32	$ 18.32	$ 35.34	$ 53.66	$ 19.43	$ 32.18	$ 51.61

Key findings regarding production economics:

- Native grass can be produced for between $35 and $55 per ton in the counties with low land rental rates, *including a land rental payment*, depending on the assumptions of the model such as yields, harvest schedule, and whether the land is grazed during non-harvest years. Production costs including a land rental payment will probably be around $40 per ton under reasonable assumptions of yield (2-4 tons/acre) and land rental payment ($20-$40 per acre) and annual harvest. This is consistent with the experience of the Chariton Valley Biomass Project, which had production costs, including a land payment, of between $41 and $75 per ton (Chariton Valley Biomass Project 2002).
- Production costs on CRP land (where CRP covers land rents) are likely to range from $20-30/ton. This is consistent with Oak Ridge National Laboratory estimates of $20 to $40 per ton (also without land payments) for the Northern Plains (Walsh et al 2003).
- Production costs with a reduced CRP payment or no CRP payment in harvest years range from $25-40/ton.
- Production costs with no CRP are around $50/ton.
- Production cost per ton is highly dependent on yield per acre. Decreased yield will dramatically increase the cost per ton regardless of the other assumptions. Clear expectations of yield will be essential in determining the economics of any native grass bioenergy project.
- Less frequent harvesting (biennial or triennial) raises the cost per ton.

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[2] A different yield assumption was made for each county: 3 tons per acre for Eddy County, ND; 4 tons per acre for Marshall County, SD and 5 tons per acre for Lincoln County, MN.

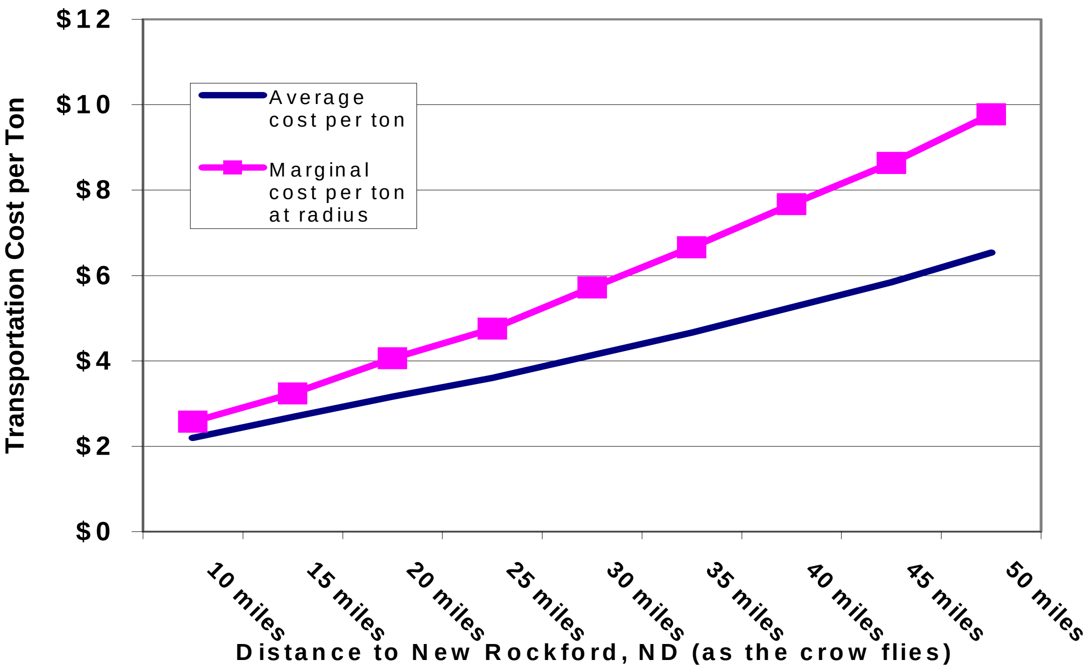
Late harvesting has several advantages. Late harvesting in the Northern Great Plains, unlike in southern climates, does not seem to lower yields (Mulkey 2005) Switchgrass harvested at Chariton Valley, Iowa, after frosts and in November had lower levels of nitrates due to seasonal movement from the leaves and stems to the roots. As Switchgrass and other native prairie grasses prepare themselves for winter, substantial quantities of nitrogen are translocated from the leaves and stems to the roots. The effect of this action is to reduce the amount of nitrogen in biomass produced from native prairie grasses. This is an important characteristic because it reduces the amount of NOx compounds formed in direct combustion of Switchgrass harvested for energy. (NOx compounds are cited as precursors for smog and a harmful emission.) Late harvested grass is also lower in ash content, which is advantageous because ash can cause problems in various utilization processes. Ash causes slagging in combustion applications, reduces the stability of pyrolysis oil for long-term storage, and may result in increased coking of pyrolysis oils that could plug various parts in diesel engines, boilers, and turbines (Shaddix 1999).

Transportation Economics: Bringing the Feedstock in for Processing

A transportation model was developed to predict the cost per ton of hauling grass from dispersed plots to a central plant within a 50 mile radius. This analysis assumed that grass was being grown on CRP land using the appropriate CRP practices for that area. The model evaluates transportation costs for a 50 mile radius around New Rockford, ND[4], a region that includes Eddy County, which was included in the production economics analysis. This region, like the regions considered for the production economics evaluation, has low land rental rates and high concentrations of land enrolled in the CRP program.

The transportation model can be adjusted for many different assumptions. Transportation costs are highly dependent on distance from the plant. **Figure 3** assumes yields of 4 tons per acre. For a complete list of assumptions see **Appendix C**.

Figure 3: Comparison of Average Cost per Ton with Marginal Cost per Ton at the Radius



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[4] The selection of New Rockford is somewhat arbitrary. It was one of several cities that met a series of criteria: located on rail and road infrastructure, near the geographic center of the selected region, and large enough to provide labor and services for an industrial plant. After a visit to the region after the study was conducted, Carrington, ND emerged as an ideal site because of its active effort to encourage industrial development (including a municipal development entity, an industrial park, as well as the experience that exists from the development of several other industrial projects).

Table 3 shows complete results for the transportation model. It demonstrates that large quantities of grass can be grown on CRP land within a 50-mile radius in the selected region of North Dakota and other regions of the country that have similar concentrations of CRP land. With marginal costs between about $3.85 and $16.77 per ton (see table 3), transportation costs are small relative to production costs, but become a larger proportion of total costs as transportation distances grow.

Table 3. Results of the Transportation Model [5]

Radius	Number of trips	Number of bales	Tons of Switchgrass	Total miles traveled	Total Travel Expenses	Average cost per ton	Marginal cost per ton	Expense per ton mile
10 miles	1,589	57,195	28,598	55,103	110,006	$3.16	$3.85	$0.10
15 miles	2,819	101,492	50,746	138,381	255,578	$4.04	$5.04	$0.08
20 miles	4,368	157,246	78,623	292,634	512,314	$4.90	$6.52	$0.07
25 miles	5,808	209,093	104,547	475,911	810,290	$5.69	$7.75	$0.06
30 miles	8,125	292,499	146,249	837,287	1,388,586	$6.65	$9.49	$0.06
35 miles	10,756	387,201	193,601	1,327,729	2,164,348	$7.59	$11.18	$0.06
40 miles	14,216	511,786	255,893	2,067,137	3,324,987	$8.66	$12.99	$0.06
45 miles	18,257	657,243	328,621	3,037,462	4,839,243	$9.72	$14.73	$0.06
50 miles	24,097	867,488	433,744	4,605,056	7,273,430	$10.96	$16.77	$0.06

Under these assumptions, more than 400,000 tons of grass can be collected within a 50 mile radius, using only grass raised on CRP land, assuming biennial harvest (more than 800,000 tons under annual harvest). This total could be much higher if additional land were recruited into a bio-industrial project.

According to Iogen (Girouard 2003) their planned cellulosic ethanol plant will use 800,000 tons of wheat straw per year to provide feedstock for a 60 million gallon per year ethanol plant. This analysis suggests that CRP land, in areas where there is a lot of CRP, could provide sufficient feedstock, by itself, for a large-scale industrial facility.

Given recent increases in petroleum prices, model assumptions for fuel price were tested. Changing from $1.50 per gallon to $3.00 per gallon diesel had little impact on transportation costs, as demonstrated in **Table 4**.

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[5] Assuming 4 tons per acre yield and $3 per gallon diesel. See Appendix C for complete assumptions.

Table 4: Transportation cost per ton of grass based on two different fuel prices.

Distance from central plant	**$1.50/gallon diesel**		**$3.00/gallon diesel**	
	Average cost per ton	Marginal cost per ton	Average cost per ton	Marginal cost per ton
5-10 miles	$2.89	$3.49	$3.16	$3.85
10-15 miles	$3.65	$4.53	$4.04	$5.04
15-20 miles	$4.40	$5.82	$4.90	$6.52
20-25 miles	$5.10	$6.90	$5.69	$7.75
25-30 miles	$5.93	$8.42	$6.65	$9.49
30-35 miles	$6.75	$9.89	$7.59	$11.18
35-40 miles	$7.69	$11.48	$8.66	$12.99
40-45 miles	$8.61	$12.99	$9.72	$14.73
45-50 miles	$9.70	$14.78	$10.96	$16.77

Yield per acre impacts the overall production from a 50 mile radius. Assuming a 4 ton per acre yield gives more then 800,000 tons. Decreasing the yield to 2 tons per acre gives more than 400,000 tons. It is important to note that a biomass project could use biomass from sources other than CRP land. In the Northern Plains this could include wheat straw, corn stover, and other residues. Despite these possibilities, CRP could likely supply an industrial-scale plant without any supplementary materials. Assuming yields of 3 tons per acre, and hence 150,000 tons of biomass, a 50,000 acre biomass project could support a 400 ton per day pyrolysis plant (discussed in more detail later). This is larger than any existing commercial pyrolysis facility, and is the largest theoretical pyrolysis plant generally discussed in academic and industry literature.

Production of Bio-Oil

Bio-oil, the product of pyrolysis, is also known as pyrolysis-oil and bio-crude, but the term bio-oil will be used in this paper. Bio-oil is a liquid fuel manufactured from the fast pyrolysis of biomass. Fast pyrolysis is distinguished from slow pyrolysis as a lower temperature, longer duration process that has been used for hundreds if not thousands of years to make charcoal and to smoke food. Fast pyrolysis heats biomass to 500-600 degrees C. in an oxygen-free environment for less than a second where it turns to gas before being quickly quenched to a liquid. This liquid is called bio-oil and is produced in yields of 60-75% of the original biomass (Shaddix 1999).

Bio-oil can be compared to conventional petroleum crude oil. Both are organic liquids that contain a complex mixture of chemicals. There is the potential to distill bio-oil just as petroleum crude is distilled to separate useful fractions. Like crude oil, some fractions will be used for different grades of fuel and some will be used to produce basic chemicals for the manufacture of materials such as plastics.

As the technology improves, the potential uses for bio-oil may increase. Bio-oil is currently used in power generation by several companies and electric utilities, both in North America and Europe. It has been tested as a liquid fuel in diesel engines and gas turbines for high efficiency peaking power generation by the Canadian company Dynamotive. The other major North American company, Ensyn, uses bio-oil primarily for manufacturing various chemical products and for generating energy as a secondary product using relatively conventional boiler technology.

Potential high-value chemicals derived from bio-oil are likely to include polyphenols for the manufacture of phenol-formaldehyde resins, calcium and/or magnesium acetate for biodegradable de-icers, levoglucosan and other anhydrosugars for ethanol production, and food flavorings (Bridgewater 1994, Bakhasi 1994, Freel and Huffman 1994). Ensyn and their partner Red Arrow already supply hydroxyacetaldehyde from bio-oil as a smoky food flavoring. Ensyn has also developed and tested a natural resin product from the polyphenol fraction (Boulard 2004) High value products can increase the revenue for a bio-oil producer and still leave behind residual bio-oil for power production.

Bio-oil is different from petroleum crude in some important ways. Unlike petroleum, bio-oil is polar and miscible with water. Unlike ethanol and biodiesel, it cannot be blended with petroleum-based fuels. Bio-oil is heavily oxygenated, making it much lower in energy density than petroleum fuels. For example, bio-oil has about half the heating value of residual and distillate oils, which may result in increased costs for transportation and storage (Bridgewater 1994). Bio-oil produced from pyrolysis of biomass presents several key challenges that must be managed whether the bio-oil is used as feedstock for chemical production or as a fuel. These challenges have been the subject of past research efforts and will likely receive substantial attention by chemical engineers in the future including the following:

Instability Issues

Bio-oil is unstable and has the tendency to undergo polymerization reactions in storage that increase the viscosity over time. It also undergoes condensation-dehydration reactions that increase the water content. Both types of reaction decrease the bio-oil's quality as a fuel.

There are two solutions to instability issues. Researchers have been successful at stabilizing bio-oil by mixing it with inexpensive low molecular weight solvents such as ethanol and methanol, typically in solutions of 10% or less. Since char particles catalyze polymerization reactions, the removal of char will also stabilize the oil. Several processes were developed at NREL to deal with char removal, and both Ensyn and Dynamotive have patented char removal processes (Diebold 2000, Mullaney 2002).

Acidity Issues

Bio-oil is mildly acidic, with a pH from 2.3-3, due to the presence of organic acids such as acetic acid and formic acid. This is similar to the pH of vinegar. Although the acidity of bio-oil is mild, it precludes the use of conventional steel for storage or processing. Stainless steel or polypropylene lines, injectors, and containers are required to effectively resist attack from bio-oil. All conventional steel parts in combustion equipment such as fuel injectors and nozzles must be replaced with stainless steel parts to prevent corrosion (Shaddix et al 1999, Diebold 2000).

High Viscosity Issues

Bio- oil has high viscosity relative to petroleum fuels, a problem that worsens in storage as polymerization reactions continuously occur. This is essentially the same problem as the stability problem discussed above, and has the same solution. Mixture with solvents such as methanol (5% solution) or ethanol (10% solution) can effectively inhibit the reactions that increase viscosity over time. However, the viscosity of bio-oil is still high for applications such as combustion in diesel engines, boilers, or turbines, so its use as fuel in these situations requires it to be pre-heated before use (Shaddix et al 1999, Diebold 2000).

Issues of Char Formation during Combustion

A common problem in combustion of bio-oil is the formation of char and coke. Due to a broad range of boiling points in bio-oil, low boiling point compounds have the tendency to form coke at lower temperatures when the rest of the compounds are stable. Char and coke formation have been reported on the valve ports and the injectors of diesel engines, and on the combustion liners of turbines, which implies an added cost for periodic cleaning. In other cases coking can interfere with the proper operation of equipment, although this can be prevented in some cases. A common problem with boilers occurs when heat transfers from the boiler to the spray gun, causing coking of the remaining bio-oil and blocking the gun. This problem can be solved by rinsing the spray gun with ethanol or another solvent when shutting down the furnace. Other parts must simply be cleaned more frequently (Shaddix 1999).

Orenda Aerospace Corporation and Dynamotive, of Vancouver, BC, have successfully tested bio-oil in a 2.5 MegaWatt gas turbine but have observed that ash can deposit on the hot gas path components resulting in reduced turbine efficiency. This is a problem with most low-grade fuels, including residual oil from petroleum, which also has high ash content. This problem is solved by using two separate systems. First an abrasive medium is injected during operation to physically “scrub’”off the deposits. In the second system, a cleaning fluid is injected while the turbine is not in operation and allowed to soak. The loosened deposits are thus removed when the engine is re-started (Thamberaj 2000). As another solution, there are efforts to fractionate different grades of bio-oil as is done with crude oil to produce higher quality fractions for more sophisticated combustion applications.

Economics of Using Bio-Oil as a Fuel

Bio-oil, despite requiring more energy and processing in production than other marketable products of biomass, creates a new niche by which to market biomass. As a liquid fuel, bio-oil can be used to generate electricity, although it is not as convenient to use as #2 diesel or #2 fuel oil.

Combustion of biomass for electricity has been more expensive than prevailing retail prices for electricity, making its commercial viability tenuous under most circumstances. In Minnesota, most biomass conversion to electricity occurs at plants dedicated to the wood products industry that produce electricity as a co-product, and partly as a means of disposing of wood waste.

Boise Cascade, for example, is primarily a paper manufacturer, but also generates electricity with a variety of waste streams including black liquor and other solid and liquid biomass waste in its Minnesota plants. In effect, when a plant utilizes waste materials with an associated disposal fee, the effective cost of the biomass fuel is close to zero or even negative.

Bio-oil may be more competitive than solid biomass, even though there are additional costs to produce it. In **Table 5**, one can compare the price of the types of biomass (corn, Switchgrass, wood) with the price of bio-oil. On a per Gigajoule basis, bio-oil is more expensive than biomass, because bio-oil is produced from biomass with yields ranging from 55-70% and requiring an energy input. [6] Bio-oil can be compared to the price of residual fuel oil, a low-grade liquid petroleum product that is used for home heating and electrical production. Bio-oil is cheaper on a per gallon basis that residual fuel oil (slightly more expensive per BTU), and much cheaper than distillate fuel oil. Unlike unprocessed biomass, bio-oil is a liquid fuel and can be compared alongside liquid petroleum products. As discussed above, bio-oil can be used in modified diesel engines and gas turbines for electrical production. Both uses have reached the pilot stage, but not the commercial stage, though electricity production with boilers is ongoing at several plants.

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[6] Accepting similar assumptions about feedstock characteristics and cost.

Table 5: Comparison of Average Price Paid by Electric Utilities and by the Entire Economy for the First 10 months of 2005 for Various Fuels with the Theoretical Price Switchgrass and Bio-oil (U. S. Energy Information Administration 2006)

Energy Source	*Theoretical Price*	*Average 2005 Electric Utility Price ($/MMBTU)*	*Average 2005 Price, all sectors ($/MMBTU)*
Gasoline			$ 17.32
No. 2 Fuel Oil		$ 11.30	$ 12.74
Natural Gas		$ 7.50	$ 7.67
Residual Fuel Oil		$ 6.57	$ 7.53
Coal		$ 1.52	
Petroleum Coke		$ 1.10	
Bio-oil	$ 8.60 [7]		
Switchgrass	$ 2.50 [8]		

This analysis uses two economic models to evaluate the cost of bio-oil, one in Bridgewater (2003) and the other in Cole Hill (2004). Bridgewater (2003) produced an equation that predicts the cost of production, or breakeven price, for bio-oil as a function of scale of the facility (wood capacity), the feedstock cost, and the energy content of the feed (lower heating value (LHV).

Figure 4: Bridgewater equation for calculating the per gallon price of bio-oil from pyrolysis (Bridgewater 2003).

$$BC = \$10.20 \times (WCAP)^{-0.3407} + \frac{(1.84 \times FC)}{WH}$$

Where:
BC= Bio-oil production cost, $/GJ, Lower heating value (LHV)
WCAP=Wood capacity, dry tonne/hour
FC=Feedstock cost, $/dry tonne
WH=Wood lower heating value (LHV)

This equation was tested against a cost accounting model produced by Cole Hill Associates for the New Hampshire Office of Energy and Planning (Cole-Hill 2004). The New Hampshire analysis was compared to a variety of other similar analyses to assure that it used similar assumptions. In some cases certain assumptions were changed. The Bridgewater equation was also modified to use short tons rather than tonnes. Other techno-economic studies were reviewed, including Gregoire and Mann 1994, Gregoire et al 1994, Mullaney et al 2002, Bridgewater et al 2002, Sandvig et al 2004, and So and Brown 1999).

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[7] Assumes $40/ton Switchgrass, 20 ton per hour plant.
[8] Assumes $40/ton Switchgrass.

Some assumptions were changed to better reflect Switchgrass or other native grasses, particularly, the lower heating value and the moisture content. Switchgrass has a slightly lower energy content and a considerably lower moisture content than wood. The assumption used for feedstock cost was $40/ton .

Once the models were adjusted, the resulting bio-oil production costs were quite similar (**Table 6**). Since the Bridgewater equation was created by performing a regression analysis on 15 economic studies, many of which were based on proprietary information that the authors cannot access, it is a useful test of any cost accounting model.

Table 6: Comparison of Cole Hill Associates Model with Bridgewater Equation for Similar Assumptions, 2004 dollars.

	Cole Hill Associates model	***Bridgewater equation***
Bio-oil Cost ($/MMBTU), assuming $40/ton biomass with 10% moisture content and a 20 ton per hour (580 ton per day) plant	$ 7.67	$ 8.50

Figure 5. Sensitivity of Bio-oil Cost to Feedstock Cost (Bridgewater)

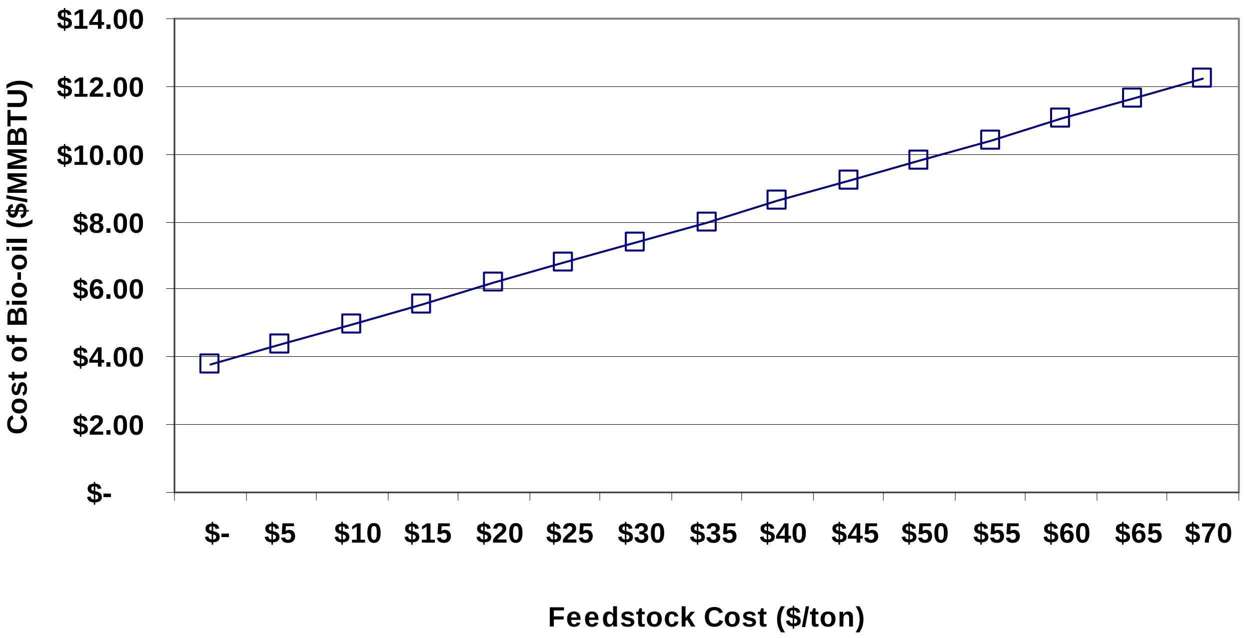


Table 7. Average 2000 Electricity Price Paid by Residential, Commercial, and Industrial Sectors, $/kWh, 2004 dollars (U.S. Energy Information Agency, 2006)

Sector	*Average price paid for electricity, $/kWh*
Residential	$0.073
Commercial	$0.061
Industrial	$0.044

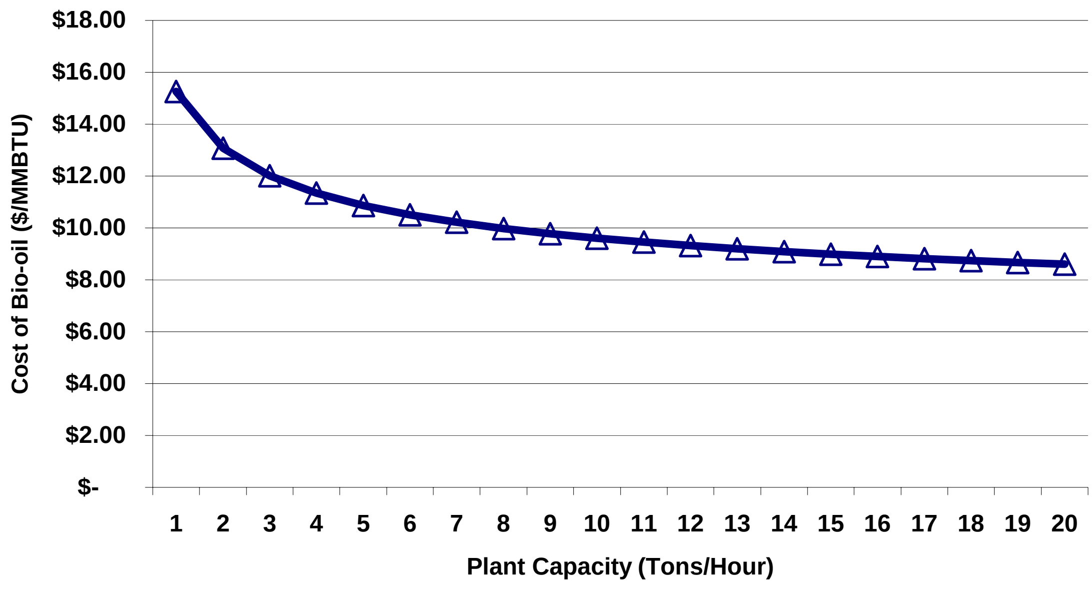
Sensitivity analysis:

The sensitivity of the Bridgewater model was tested over its three main assumptions: feedstock cost, lower heating value and scale of the facility in tons per hour.

The sensitivity to feedstock cost is demonstrated in **Figure 5**. Bio-oil cost shows a positive linear relationship with feedstock cost. This is consistent between the Bridgewater and Cole Hill models.

Figure 6 shows the influence of the scale of the facility on cost (for $40/ton biomass). The figure demonstrates decreasing cost reductions for increasing scale of operations. The Bio-oil cost levels off around $8/MMBTU. This is slightly more expensive than residual fuel oil and natural gas (at prices paid by electric utilities) and considerable cheaper than distillate fuel. Of course, the fuel upgrading that would be necessary for bio-oil to compete directly with higher quality fuels like #2 diesel and gasoline in more sophisticated engines will increase the cost, but this figure demonstrates the ability of bio-oil to accept additional costs for upgrading.

Figure 6: Sensitivity of Cost of Bio-oil ($/GJ) to Plant Capacity



Economics of Producing Chemicals from Native Prairie Grasses

To date, commercial and industrial interests have concentrated their efforts on woody feedstocks due to their availability and their more favorable chemistry with lower levels of potassium in the feedstock and the resulting bio-oil. An active commercial example is the activity of Red Arrow in refining smoky flavor additives from the hydroxyacetaldehyde (HA) fraction of bio-oil. Review of the yields of intermediate chemicals derived from bio-oil produced from native prairie grasses offers some insight into the prospects for economic feasibility of pyrolysis using these feedstocks. Chemical yields reported by the Energy and Environmental Research Center, (Olson et al 2006) are useful in evaluating whether or not production of chemicals from bio-oil is technically and economically feasible. **Table 8** contains the yields of bio-oil, gas, and char on "as fed" as well as "moisture and ash free bases for both Switchgrass and Big Bluestem.

Table 8.

Pyrolysis Product Yields

	Bio-Oil Yield, wt%		**Gas Yield, wt %**		**Char Yield, wt%**	
Feedstock	As Fed	MAF	As Fed	MAF	As Fed	MAF
Switchgrass	68	65	22	24	10	11
Big Blue Stem	71	68	22	24	7	8

From the table it is evident that Big Bluestem yields more bio-oil than Switchgrass in this series of tests. Recall that energy is available for combustion from the char and gasses formed by pyrolysis.

Table 9 focuses on the bio-oil and the key constituents of interest for extraction as valuable chemicals. Note that the bio-oil resulting from pyrolyzing Big Bluestem yields higher amounts of the most important constituents, which are HA, phenol, and AHG. The bio-oil from the Big Bluestem is superior (lower) in the amount of resins over Switchgrass. More resins seem to result at the expense of higher HA and AHG yields, especially in the case of Switchgrass.

Table 9.

Key Bio-Oil Constituent Yields

	Switchgrass		Big Bluestem	
Material	Wt% in Bio-Oil	Yield, wt% of MAF Grass (a)	Wt% in Bio-Oil	Yield, wt% of MAF Grass
HA(b)	8	5	13	9
Anhydroglucose	5	4	9	6
Acetic Acid	2	1	8	5
Formic Acid	2	1	6	4
Phenols	1	1	5	3
Resins-pws ©	7	5	6	4
Resins-wi (d)	56	37	35	23
Water	18	11	20	13

a Based on MAF weight of grass fed to pyrolysis reactor
b Hydroxyacetaldehyde
c Partially water-soluble
d Water-insoluble

Efforts to Hydrolyze Anhydroglucose into Fermentable Sugars

Using a process developed by EERC, which is in the process of securing patent approval, a solid acid catalyst was used to hydrolyze the anhydroglucose molecules into simple sugars, which theoretically should be fermentable. The reported conversion of anhydroglucose from both Switchgrass and Big Bluestem to simple sugars was determined to be very complete (Olson, et al. 2006).

Efforts to Ferment Simple Sugars Split from Anhydroglucose

Samples of the simple sugars hydrolyzed from the AHG for both Switchgrass and Big Bluestem were sent to the Biotechnology Center at the University of Minnesota for fermentation studies. Various yeasts and bacteria were tested, but minimal levels of fermentation to ethanol occurred from sugars derived from either the Switchgrass or the Big Bluestem, apparently due to toxic residues in the substrates. In contrast, EERC was more successful in producing ethanol from the simple sugars hydrolyzed from AHG derived from wood chips. Without success in producing ethanol from the AHG fraction of the native prairie grasses, that constituent of bio-oil has little value, and the economics of deriving a greater assortment of valuable chemicals are reduced.

Value of Extracting Chemicals from Bio-Oil

Lacking ethanol production based on the AHG fraction of bio-oil, one must consider the possibility of extracting various constituents of bio-oil and perhaps combusting the remainder. Key considerations regarding the extraction of valuable components are the physical attributes of the remaining bio-oil. It would be unwise to remove too much of various constituents and harm the pumpability and combustion properties of the residual bio-oil. The key components for consideration in bio-oil and their potential utilization and value follow:

Hydroxyacetaldehyde (HA) HA is currently collected from bio-oil pyrolyzed from wood products at facilities of Red Arrow in Wisconsin. With additional processing, various food flavoring products are produced and sold. It is uncertain how much more HA can be utilized for the food flavoring market. Another alternative use for HA might be as a replacement chemical for ethanolamine or ethylene oxides, which are used as dispersing agents. Many of these are used in detergents or as agents for gas purification. Prices seem to range from $.56 to $.67 per pound depending whether the form sold is monoethanolamine or diethanolamine or triethanolamine, with higher prices for the more complex molecules. The size of this market is 1.295 billion pounds per year in the U.S. for the three forms of the molecule.[9]

Phenol This chemical is often used to make bisphenol-A as well as phenol-formaldehyde (P-F) resins such as those used to bind various forest products, for which there is a large market.[10] The very complex mixture of substituted phenols that occurs in the bio-oil fraction can be converted to a similar P-F resin. Prices have ranged from $.45 per pound in 2003 to $.68 per pound in 2005 and are highly correlated with crude oil prices.[11]

Anhydroglucose (AHG) With no current way to practically ferment the simple sugars, the value of AHG is difficult to estimate if these sugars can't be fermented.

Formic Acid and Acetic Acid These are relatively low value organic acids that could be extracted as a mixture to make de-icing products after mixing with lime and other chemicals (Olson 2006).

Water-soluble Resins and Water-insoluble Resins The resins have little value and may be burned in some situations with caloric density similar to wood (Olson 2006).

Water The water in bio-oil is considered to have no commercial value, although its presence makes bio-oil easier to pump, transport, and store.

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[9] Chemical Profiles. Website: www.the-innovation-group.com/ChemProfiles/Ethanolamines.htm

[10] Chemical Profiles. Website: www.the-innovation-group.com/ChemProfiles/Phenol.htm

[11] Evans, Robert and Doris McCormick. River Valley Biomass Refinery Market Study. 2006. Website: http://www.mainefdc.org/pdf/presentation.pdf , slide 34.

Determining the Merit of Extracting Chemicals from Bio-Oil

An electronic spreadsheet was constructed to determine whether sufficient value can be added to bio-oil by attempting to extract, purify, and sell various constituents of bio-oil. The following spreadsheet, **Figure 7**, offers a framework to determine the merit of trying to economically produce chemicals from bio-oil derived from native prairie grasses. As better data emerge, it will be possible to recalculate the merit of chemical extractions from bio-oil. Because there is some prospect for utilizing bio-oil as a fuel already, the potential financial surplus or deficit from further processing to make and segregate valuable chemicals can be measured. Another possibility would be to extract the HA and phenols for further refining with utilization of the remainder as a modified bio-oil. Indications are that the modified bio-oil, although lower in volume, would still be useful as a fuel for gasifiers or boilers, much as the case in Manitowoc, Wisconsin, where bio-oil produced by Red Arrow was relieved of its HA fraction before being combusted in a utility generator with coal (Sturzl 1997).

Using the Spreadsheet

The spreadsheet permits one to apply numerous assumptions to determine the preliminary economics of extraction of chemicals from bio-oil. The costs to produce, transport, pre-treat and pyrolyze the biomass are estimated. Then the spreadsheet allows one to determine the potential value of chemicals to be derived from the bio-oil before consideration of additional chemical segregation and refining costs.

Cells that are shaded yellow can accept values input by the user of the spreadsheet. Cells shaded in green can accept words. Starting at the top of the worksheet, one must establish cost of the feedstock standing in the field per ton, estimate a harvest cost per ton, and estimate the transportation cost to a pyrolysis plant. Then it is necessary to make assumptions about the delivery moisture and the target moisture that is ideal for the start of the pyrolysis. The cost to remove a point of moisture from a ton of feedstock is also an assumption input as well as the assumed cost to grind up the feedstock to the proper size for pyrolysis. Other pre-processing steps could be added, if necessary, in the future.

The next assumptions concern the capital cost of the pyrolysis unit, its expected life (15 years in this case), the percent debt, the interest rate charged, and the years of the loan. Figures from a New Hampshire study were used for the cost of the pyrolysis unit and the throughput assumed per year (Farag et al. 2002). This study was also used to establish the costs of repairs, labor, electricity, and nitrogen purchased. Because sufficient energy should be available to run the pyrolysis reaction from gasses and char produced, not expense was made for natural gas. Factors for taxes, insurance, were based upon studies of ethanol plants costs in these categories (Tiffany and Eidman, 2003). Ash disposal costs were based upon figures reported for landfilling ash from coal-fired power plants. Based on the assumptions established, the spreadsheet calculates the cost of $112.28 applied to get a ton of Big Bluestem through the pyrolysis unit, which in this case yields 1420 pounds of bio-oil based on the 71% yield for Big Bluestem.

The percentages of the assumed constituents of the bio-oil derived from Big Bluestem are entered in the yellow shaded cells for HA, AHG, acetic acid, formic acid, phenols, resins, and water. In addition, yellow shaded cells to the right of the chemical constituents accept the valuations that are contemplated when extracted from the bio-oil. The examples for Big Bluestem and Switchgrass portrayed in **Figure 7** and **Figure 8** utilize values for the constituent chemicals that follow:

	Value
Hydroxyacetaldehydes (HA)	$.35 per lb.[12]
Anhydroglucose (AHG)	0 per lb.[13]
Acetic and Formic Acids	$.10 per lb.[14]
Phenol	$.45 per lb.[15]
Resins (partially water soluble and water insoluble)	$.04 per lb.[16]

No attempt is made to determine the necessary cost of extraction equipment or refining, which may or may not occur in close proximity to the pyrolysis plant. What is calculated is a gross margin before capital and operating costs required to extract and purify the target chemicals.

This gross margin is sufficient to guide individuals and business considering extraction of chemicals from bio-oil. Because bio-oil has significant value as a fuel that can substitute for lower quality distillate fuels, the calculation of the gross margin suggests when chemical extraction is economically prudent. In the Big Bluestem case portrayed in **Figure 7**, the gross margin seems small at $28.45, which suggests that at assumed costs, prices and yields bio-oil will probably be used as a fuel, not as a source of chemicals. This exercise and the changes that may occur in the chemical industry as it adjusts to more expensive petroleum and natural gas suggest that there may be potential for pyrolysis-derived chemicals, if a sufficient critical mass of firms chooses to produce chemicals from biomass by using pyrolysis.

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[12] HA has a limited market at present, although Red Arrow and its partners have found these chemicals useful in making liquid smoke and flavorings.

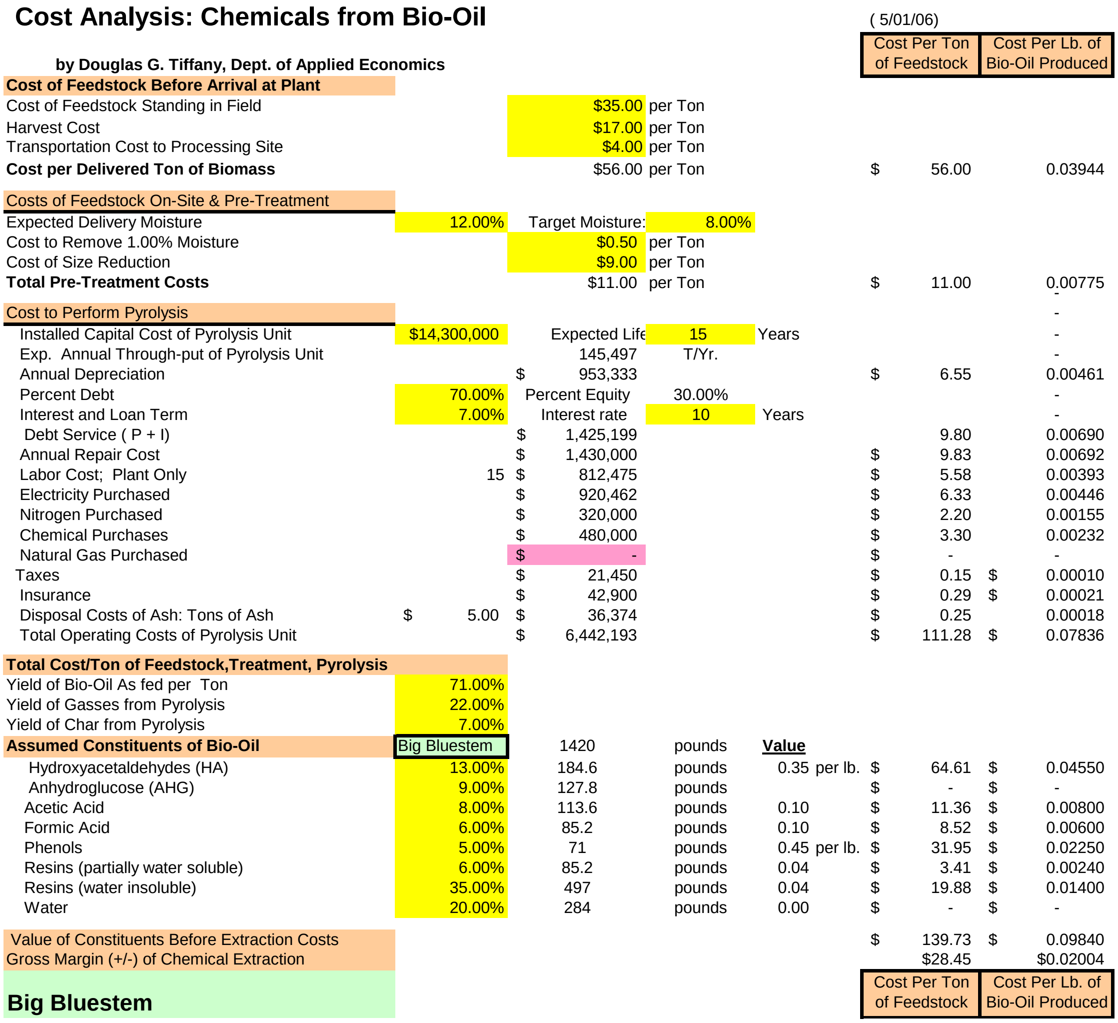
[13] No value was listed for the anhydroglucose due to the current poor fermentability of these sugars after hydrolysis.

[14] Acetic and Formic Acid were assumed to be extractable as a mixture with the potential for use as a deicer of equipment, roads, and runways, following efforts to reduce corrosive properties.

[15] Evans and McCormick. 2006 . "Phenol Market Data." P. 98..

[16] Resins are considered as a fuel source and are valued on a per pound basis equal to corn valued at $2.25 per bushel.

Figure 7.



Cost Analysis: Chemicals from Bio-Oil

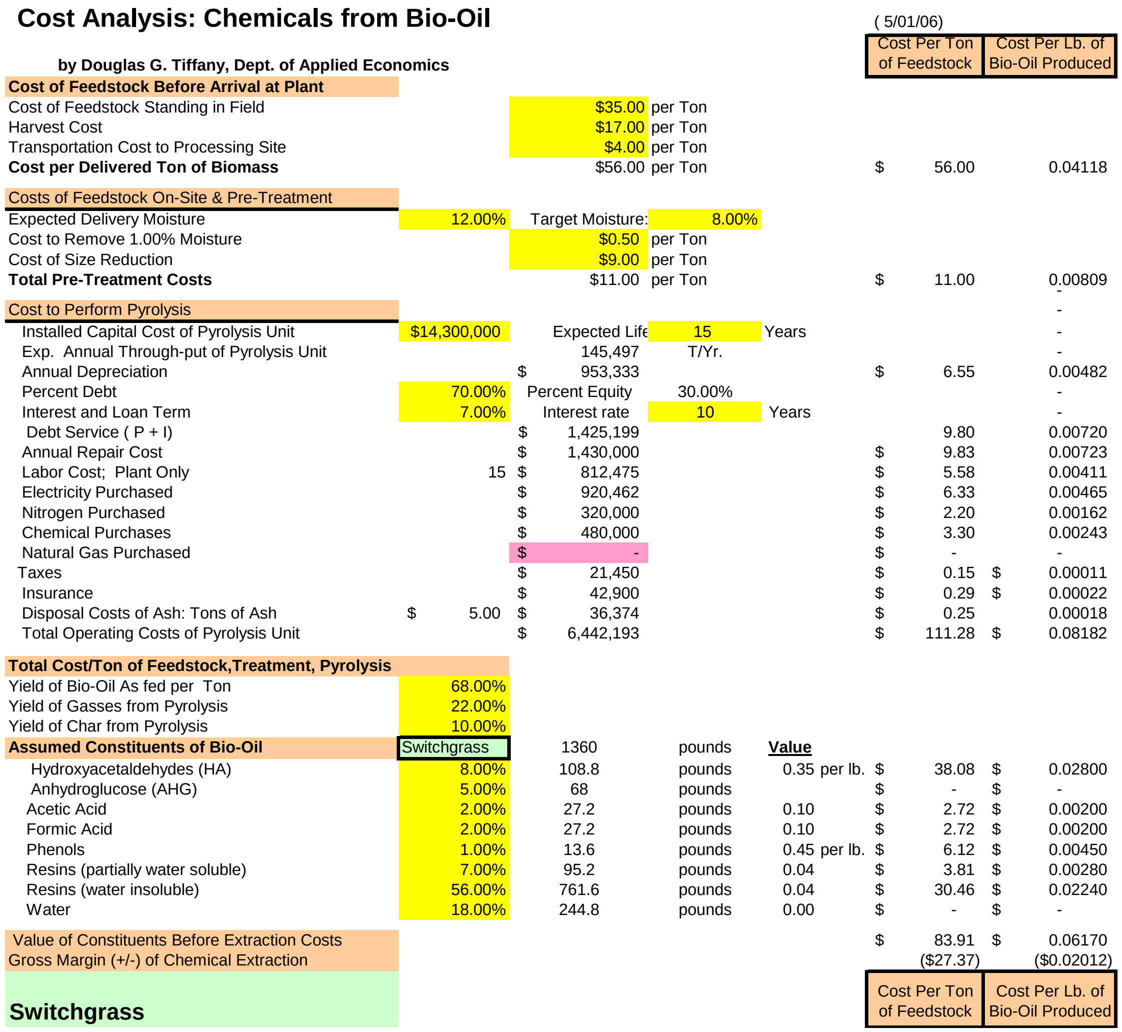
(5/01/06)

by Douglas G. Tiffany, Dept. of Applied Economics

					Cost Per Ton of Feedstock	Cost Per Lb. of Bio-Oil Produced
Cost of Feedstock Before Arrival at Plant						
Cost of Feedstock Standing in Field		$35.00	per Ton			
Harvest Cost		$17.00	per Ton			
Transportation Cost to Processing Site		$4.00	per Ton			
Cost per Delivered Ton of Biomass		$56.00	per Ton		$ 56.00	0.03944
Costs of Feedstock On-Site & Pre-Treatment						
Expected Delivery Moisture	12.00%	Target Moisture:	8.00%			
Cost to Remove 1.00% Moisture		$0.50	per Ton			
Cost of Size Reduction		$9.00	per Ton			
Total Pre-Treatment Costs		$11.00	per Ton		$ 11.00	0.00775
Cost to Perform Pyrolysis						-
Installed Capital Cost of Pyrolysis Unit	$14,300,000	Expected Life	15	Years		-
Exp. Annual Through-put of Pyrolysis Unit		145,497	T/Yr.			-
Annual Depreciation		$ 953,333			$ 6.55	0.00461
Percent Debt	70.00%	Percent Equity	30.00%			-
Interest and Loan Term	7.00%	Interest rate	10	Years		-
Debt Service (P + I)		$ 1,425,199			9.80	0.00690
Annual Repair Cost		$ 1,430,000			$ 9.83	0.00692
Labor Cost; Plant Only	15	$ 812,475			$ 5.58	0.00393
Electricity Purchased		$ 920,462			$ 6.33	0.00446
Nitrogen Purchased		$ 320,000			$ 2.20	0.00155
Chemical Purchases		$ 480,000			$ 3.30	0.00232
Natural Gas Purchased		$ -			$ -	-
Taxes		$ 21,450			$ 0.15	$ 0.00010
Insurance		$ 42,900			$ 0.29	$ 0.00021
Disposal Costs of Ash: Tons of Ash	$ 5.00	$ 36,374			$ 0.25	0.00018
Total Operating Costs of Pyrolysis Unit		$ 6,442,193			$ 111.28	$ 0.07836
Total Cost/Ton of Feedstock,Treatment, Pyrolysis						
Yield of Bio-Oil As fed per Ton	71.00%					
Yield of Gasses from Pyrolysis	22.00%					
Yield of Char from Pyrolysis	7.00%					
Assumed Constituents of Bio-Oil	Big Bluestem	1420	pounds	**Value**		
Hydroxyacetaldehydes (HA)	13.00%	184.6	pounds	0.35 per lb.	$ 64.61	$ 0.04550
Anhydroglucose (AHG)	9.00%	127.8	pounds		$ -	$ -
Acetic Acid	8.00%	113.6	pounds	0.10	$ 11.36	$ 0.00800
Formic Acid	6.00%	85.2	pounds	0.10	$ 8.52	$ 0.00600
Phenols	5.00%	71	pounds	0.45 per lb.	$ 31.95	$ 0.02250
Resins (partially water soluble)	6.00%	85.2	pounds	0.04	$ 3.41	$ 0.00240
Resins (water insoluble)	35.00%	497	pounds	0.04	$ 19.88	$ 0.01400
Water	20.00%	284	pounds	0.00	$ -	$ -
Value of Constituents Before Extraction Costs					$ 139.73	$ 0.09840
Gross Margin (+/-) of Chemical Extraction					$28.45	$0.02004
Big Bluestem					Cost Per Ton of Feedstock	Cost Per Lb. of Bio-Oil Produced

A similar analysis was conducted using the spreadsheet based on the trials to produce bio-oil from Switchgrass, which is less favorable than Big Bluestem. Those results are shown in **Figure 8** and reveal that total costs through the pyrolysis unit are identical. However, the overall bio-oil yield and the lower yields of the more valuable individual constituents result in a gross margin of -$27.37 (negative) per ton of Switchgrass, which is certainly unfavorable in light of the additional costs to extract and refine the target chemicals that will be needed. At the commercial level, it is unlikely to have pure stands of either of these native prairie grasses. Agronomic factors such as stand longevity and the ability to yield well under variable conditions may guide the decision to favor particular species in a forage mixture.

Figure 8.



Cost Analysis: Chemicals from Bio-Oil

by Douglas G. Tiffany, Dept. of Applied Economics

(5/01/06)

					Cost Per Ton of Feedstock	Cost Per Lb. of Bio-Oil Produced
Cost of Feedstock Before Arrival at Plant						
Cost of Feedstock Standing in Field		$35.00	per Ton			
Harvest Cost		$17.00	per Ton			
Transportation Cost to Processing Site		$4.00	per Ton			
Cost per Delivered Ton of Biomass		$56.00	per Ton		$ 56.00	0.04118
Costs of Feedstock On-Site & Pre-Treatment						
Expected Delivery Moisture	12.00%	Target Moisture:	8.00%			
Cost to Remove 1.00% Moisture		$0.50	per Ton			
Cost of Size Reduction		$9.00	per Ton			
Total Pre-Treatment Costs		$11.00	per Ton		$ 11.00	0.00809
Cost to Perform Pyrolysis						-
Installed Capital Cost of Pyrolysis Unit	$14,300,000	Expected Life	15	Years		-
Exp. Annual Through-put of Pyrolysis Unit		145,497	T/Yr.			-
Annual Depreciation		$ 953,333			$ 6.55	0.00482
Percent Debt	70.00%	Percent Equity	30.00%			-
Interest and Loan Term	7.00%	Interest rate	10	Years		-
Debt Service (P + I)		$ 1,425,199			9.80	0.00720
Annual Repair Cost		$ 1,430,000			$ 9.83	0.00723
Labor Cost; Plant Only	15	$ 812,475			$ 5.58	0.00411
Electricity Purchased		$ 920,462			$ 6.33	0.00465
Nitrogen Purchased		$ 320,000			$ 2.20	0.00162
Chemical Purchases		$ 480,000			$ 3.30	0.00243
Natural Gas Purchased		$ -			$ -	-
Taxes		$ 21,450			$ 0.15	$ 0.00011
Insurance		$ 42,900			$ 0.29	$ 0.00022
Disposal Costs of Ash: Tons of Ash	$ 5.00	$ 36,374			$ 0.25	0.00018
Total Operating Costs of Pyrolysis Unit		$ 6,442,193			$ 111.28	$ 0.08182
Total Cost/Ton of Feedstock,Treatment, Pyrolysis						
Yield of Bio-Oil As fed per Ton	68.00%					
Yield of Gasses from Pyrolysis	22.00%					
Yield of Char from Pyrolysis	10.00%					
Assumed Constituents of Bio-Oil	Switchgrass	1360	pounds	**Value**		
Hydroxyacetaldehydes (HA)	8.00%	108.8	pounds	0.35 per lb.	$ 38.08	$ 0.02800
Anhydroglucose (AHG)	5.00%	68	pounds		$ -	$ -
Acetic Acid	2.00%	27.2	pounds	0.10	$ 2.72	$ 0.00200
Formic Acid	2.00%	27.2	pounds	0.10	$ 2.72	$ 0.00200
Phenols	1.00%	13.6	pounds	0.45 per lb.	$ 6.12	$ 0.00450
Resins (partially water soluble)	7.00%	95.2	pounds	0.04	$ 3.81	$ 0.00280
Resins (water insoluble)	56.00%	761.6	pounds	0.04	$ 30.46	$ 0.02240
Water	18.00%	244.8	pounds	0.00	$ -	$ -
Value of Constituents Before Extraction Costs					$ 83.91	$ 0.06170
Gross Margin (+/-) of Chemical Extraction					($27.37)	($0.02012)
Switchgrass					Cost Per Ton of Feedstock	Cost Per Lb. of Bio-Oil Produced

If technical improvements were to result in readily fermentable sugars hydrolyzed from AHG, then it would be appropriate to attribute some value to these constituent chemicals in the bio-oil derived from Big Bluestem and Switchgrass. As mentioned previously, the process developed and used by EERC reported a 90% conversion from AHG to sugars (Olson et al. 2006). Those sugars could be fermented to ethanol by yeast at rates as high as 51%, theoretically. Applying those factors to the examples portrayed for Big Bluestem and Switchgrass and valuing ethanol at $2.00 per gallon would improve the gross margins by $17.58 per ton of Big Bluestem and $9.50 per ton of Switchgrass. In both cases the enhanced potential for ethanol production would be favorable, resulting in the gross margins of $46.30 and -17.87 (negative) per ton for Big Bluestem and Switchgrass, respectively. Higher comparative per acre yields of and/or lower field production costs of Switchgrass could lessen or even reverse the advantage Big Bluestem seems to enjoy in this analysis. It is difficult find much data that compares the biomass yields of native prairie grasses in pure stands.

Other Options for Utilizing Native Prairie Grasses

In addition to processing options for native prairie grasses that involve pyrolysis, it is useful to review other possible technologies that may emerge as economical choices. In this section of the paper we shall review some of the other leading possibilities that are under consideration. Successful advances by some of the "competing technologies" may offer higher returns than pyrolysis, so they should be briefly discussed. Lignocellulosic production of ethanol and the option of co-firing native prairie grasses in a coal-fired power plant are the two most prominent alternatives.

Lignocellulosic Ethanol from Native Prairie Grasses

The National Renewable Energy Lab (NREL) has been in the forefront of efforts to perfect lignocellulosic ethanol processing. NREL Research teams headed by Wooley and Aden modeled the economics making ethanol by utilizing wood chips and corn stover, respectively. These two prominent studies identified three key parameters that determine the cost of ethanol produced by biomass. The three parameters are 1) feedstock price delivered to the plant, 2) ethanol yield per ton of biomass, and 3) enzyme cost per gallon of ethanol produced. The two research teams were able to consider near term and longer term ethanol yields and enzyme prices. **Table 10** summarizes the resulting ethanol prices based on assumptions for ethanol yields and enzyme costs when applied to corn stover or wood chips costing $50 per ton.

Table 10.

Ethanol Cost per Denatured Gallon Derived from $50 Corn Stover

Conversion Rates		Enzyme Cost	Cost/ Denatured Gallon
Future	89.7 Gal./ Ton	$0.10 per Gal. of Ethanol	$1.25
		$0.25 per Gal. of Ethanol	$1.40
Base	67.8 Gal./ Ton	$0.10 per Gal. of Ethanol	$1.65
		$0.25 per Gal. of Ethanol	$1.79

(Source: National Renewable Energy Laboratory Study)

This table of parameters, demonstrates how improvements in conversion rates and reductions in enzyme cost per gallon of ethanol produced can work to reduce the resulting cost of lignocellulosic ethanol. Some favorable reports by enzyme companies Novozymes and Genencor reduce enzyme costs to the area of $.10 per gallon. Conversion rates have been rumored to be near 80 gallons per ton. Using a conservative (high) feedstock price, with these conversion rates, results in ethanol prices that may approach costs of corn-based ethanol, particularly if corn prices rise in response to higher nitrogen and diesel fuel costs. Short corn crops coupled with high gasoline prices and natural gas prices would hasten the conversion of U.S. ethanol production toward lignocellulosic methods. There are challenges to be met with lignocellulosic ethanol, but success has been achieved in laboratories using these feedstocks. Of particular interest are pre-treatment techniques that adequately prepare the feedstock for fermentation without residual traces of toxic agents that harm fermenting organisms. From a commercial point of view, lignocellulosic ethanol plants would cost three times as much per gallon of capacity and would also be in the business of selling electricity (Wooley et al, Aden et al, Tiffany and Eidman 2004).

In Canada, the company Iogen has been pursuing lignocellulosic ethanol with major emphasis on wheat straw as a feedstock. This firm, which has now partnered with Shell, has built a test facility capable of annually producing one million gallons of ethanol from wheat straw. Reports by representatives of this company indicate that they are contracting for straw in Idaho and in Manitoba for future ethanol production.

Electricity Production from Combustion of Native Prairie Grasses

Electricity is generally considered to be the lowest value product that can be produced from biomass. Electricity is typically produced as one of several products. Examples in Minnesota include production of electricity using wood waste from the wood products industry, and production of combined heat and power at St. Paul’s District Energy plant. In both cases, the overall economics of electricity production are improved by the sale of other, higher value products such as heat/cooling or wood products.

Producing only electricity from biomass is unlikely to be cost-competitive in this region due to the low cost of other energy resources. The direct competitor is coal, which has roughly twice the energy content per ton as Switchgrass. At $50 per ton of Switchgrass, coal is also about half the price, making Switchgrass about four times the cost of coal on a BTU basis due to the lower energy content of a ton.

Despite the obvious economic barriers, the Chariton Valley project is focused on co-firing biomass with coal in a large pulverized coal plant. In April of 2006, this project was in the middle of a large-scale test-firing. The Ottumwa Generating Station in Southern Iowa was co-firing about 2% Switchgrass with coal, involving about 14 tons of Switchgrass per hour. Producing, transporting, and handling that quantity of Switchgrass is a logistical achievement. Whether or not co-firing becomes the technology of choice for the future of native grass-to-energy projects, all future projects will benefit from this experience (Chariton Valley Biomass Project 2002).

Ancillary Economics Benefits, Alternative Income Streams of Native Prairie Stands

There are other potential sources of income from planting native grasses, beyond the potential revenue from harvesting and selling them as energy crops. Some of these are currently being realized, and some are not. We do not evaluate the economic impact of these practices, but they should be mentioned because they have emerging importance. Most of these additional sources of income are consistent with harvesting of grasses in a manner that is not detrimental to the stand diversity and survivability.

Current sources of income from native grasses include CRP, bird hunting leases and seed sales. CRP has been discussed elsewhere. Leasing land for bird hunting is a common practice in North and South Dakota. This practice could be consistent with harvesting only if harvesting did not negatively impact bird populations. This would certainly require synchronizing harvest time and harvest frequency with bird nesting. This probably involves late fall or early spring harvesting, and less than annual harvesting. Some landowners may be able to sell native grass seed to others seeking to establish native grass plots, but this option may require changes in laws regulating seed sales. Harvest of native prairie grass seeds would involve cutting the grass at the right time of year when the grasses are headed-out and before they shatter. Having a multi-species stand would considerably complicate this process, since different species head and shatter at different times of the year.

A source of income that is not currently being realized is the sale of carbon permits. This was discussed elsewhere in the paper. If a cap-and-trade system were implemented for greenhouse gasses, there would be the potential for land owners to receive payments for stimulating carbon sequestration in soils by planting and harvesting native grasses (Barnes, 2001).

Recommendations for Further Study

This has been a modest reconnaissance study that sought to quickly determine the opportunities to utilize native prairie grasses by using a novel processing technology. As class members and instructors grappled with the problems, certain topics surfaced and should be further explored by others, including the following:

- More data is needed on Switchgrass yields on land of varying quality in the Northern Great Plains to determine the viability of a native-grass energy industry. This research has demonstrated that the economics of grass production are highly dependent on yields, and very low yields (lower than 2 tons per acre) make the viability of this project highly unlikely without considerable subsidies. Yield variability can be expected to be substantial, especially on marginal land where conventional crop production has been unsuccessful. An understanding of local and regional yield variability of native prairie grasses will be critical to establishing any businesses based on the production of prairie biomass.

- Site visits to CRP land in the regions under consideration would be desirable to evaluate the quality of existing native grasses and the possibility of harvesting. It is possible that high-quality native prairie stands already exist, which would considerably lower establishment costs. On the other hand, much of the land may have characteristics such as severe slopes, bumpiness, rocks, or seasonal wetness that hinder mechanical harvesting.

- It would be desirable to survey landowners who are enrolled in the CRP program in order to determine their willingness to participate in a biomass project involving native prairie species of grass.

- Although the production economics analysis reveals that the CRP program is an effective means of subsidizing grass production for energy, this study doesn’t determine the level of subsidy that would be necessary to allow an industry to exist based on that production of native grasses.

- This research demonstrates that there is a trade-off between the lower land rental rates of marginal lands and the lower yields that may result. Both high land rental rates and low yields raise the cost per ton to produce grasses. This relationship must be explored to determine the most economical route for producing grass as an energy crop.

- There is a large difference in production costs depending on assumptions about how long the stand survives without replanting. More research should be done to determine how long a stand survives without replanting under conditions of regular harvesting for energy. If stands can survive indefinitely and be harvested, costs over the long term will be lowered considerably by allowing establishment costs to be amortized over more years rather than only ten or twenty.

Conclusions

Native prairie grasses can be produced on marginal lands in the Upper Great Plains for an unsubsidized cost of around as high as $50 per ton on CRP-subsidized (no land rental) as low as $20/ton. An ideal region for grass production combines low land rental with moderate yields, and proximity to a good plant site. Transportation cost within a 50 mile radius in an ideal biomass production region in North Dakota will be between $3.16 and $10.96 per ton, depending on the radius. Storage costs in drier areas of the Northern Great Plains should be minimal, as they are for hay stored for cattle feed.

Feedstock costs delivered to a plant are likely to run from $35-$65 per ton including storage and transportation. Native prairie grass can be converted to bio-oil at rates from 68-71%, depending upon the species of grasses. The bio-oil has a value as a replacement for low-grade distillate fuels and can be combusted in boilers, combustion turbines, or even diesel engines. Bio-oil needs special additives and treatment to reduce side-reactions in storage. Experience in pyrolyzing wood suggests that this technology can be applied to native prairie grasses. However, the potassium in fall-harvested prairie grasses serves as a catalyst that reduces yields of bio-oil. In this study, it was found that over-wintered native prairie grasses had potassium levels at levels low enough for favorable pyrolysis.

Review of USDA data reveals that availability of large amounts of CRP land could be utilized in production of native prairie grasses. Significant environmental services in the form of reduced soil erosion, improved water quality, enhanced carbon sequestration, and wildlife habitat enhancement have been observed on CRP acres seeded to native prairie grasses.

Based on the constituents of bio-oil derived from native prairie grasses in this study, fermentation of simple sugars derived from the AHG fraction of bio-oil is impractical at this time due to residual toxic agents. It may be economical to extract the HA and phenol fractions and perhaps the formic and acetic acid fractions. However, more chemical engineering research will be needed to determine proper techniques to apply to bio-oil.

Bio-oil and modified bio-oil (lacking phenols and HA fractions) may be a satisfactory fuel in boilers and combustion turbines for producing electricity. Such electricity would be considered as originating from a qualified facility under PURPA rules and could enjoy attractive tariffs when sold to nearby utilities.

There are other possibilities to utilize native prairie grasses ranging from co-firing to ligno-cellulosic ethanol production. When considering one technology choice, one is wise to consider the prospects for the emergence of competing technologies that can utilize the native prairie grasses that can be grown on the Northern Great Plains.

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Appendix A Literature Review of Production Costs

Production Cost most applicable to Northern Great Plains region	**Location of study**	**Range of Production costs**	**Unsubsidized cost**	**Cost subsidized by CRP (minus land rental payment**	**Other**	**Source**
$44.36 - $118.48/ton (assuming $25-$50/acre land rental and 1.5-4 ton/acre yield)	Southern Iowa	$44.36 - $151.81/ton (land rental from $25 - $100/acre, yield from 1.5 to 6 tons/acre)	Same as first column	Not indicated in study	The overall cost per ton would be decreased if establishment costs were amortized over a longer time period then 11 years (say 20 years)	Duffy and Nanhou
	Southern Iowa	$44/ton (assumption used for fuel supply predictions – considered "best case")	$44/ton	Not indicated in study		Chariton Valley Biomass Project, Draft Fuel Supply Plan 2002
	Southern Iowa	$41-$75/ton			The range of estimated production costs for the Chariton Valley Biomass Project	Chariton Valley Biomass Project, FAQ
	Southern Iowa	$45-60/ton (current non-energy selling price of Switchgrass)	$45-60/ton	Not indicated in study	Two farmers were able to sell Switchgrass at this price to Department of Transportation and local construction companies, competing in the existing hay market	Hipple and Duffy
$60/ton with full land rental payment $46/ton with 40% land rental reduction $35/ton fully subsidized by CRP (assuming 3 ton/acre yield)	Nation-wide analysis	$14 to $60 depending on level of subsidy and yield	$29/ton(7 tons/acre) - $60/ton(3 tons/acre)	$14/ton(7 tons/acre) to $35/ton (3 tons/acre)		Walsh et al 1996

Appendix A. (cont.) Literature review of yield, application to Northern Great Plains

Yield assumption most applicable to Northern Great Plains Region	**Total range of estimates**	**Sites**	**Relevance to present study**	**Other notes**	**Source**
0.8 – 2.7 tons/acre	same	Brule, Gregory, Marshall, and Moody Counties in eastern South Dakota	High relevance due to Northern Plains sites, study uses CRP land.	Yields are responsive to moderate nitrogen addition, with diminishing returns to higher levels of addition. Harvesting at anthesis rather than after killing frost increases yields, but at the expense of stand survival	Mulkey et al 2004
Moderate land: 1.3-2.7 tons/acre Better land: 2.7-4.5 tons/acre	0.45-5.4 tons/acre	Eastern and Central South Dakota	High relevance due to Northern Plains sites.	Using well-adapted local varieties is important. The higher yielding southern varieties had decreased stand survival. Later harvesting (August – October) gives better yields.	Boe 2004
Most study sites were in southern regions, with expected higher yields	4.5-6.7 tons/acre is typical. Yields as high as 9 tons/acre were found. Northern cultivar Cave-In-Rock had average yields of 5 tons/acre	18 field sites, primarily in Southern and South-eastern states, but also in NE, SD, IA, WI, MI and MA.	This study probably gives a poor indication of likely yields in the Northern Great Plains. Southern climates have higher yields.	A two-cut per year system can give higher yields, but uses more nitrogen and wouldn’t work in drier climates (like those of the northern Great Plains).	McLaughlin et al
2.5-4.5 tons/acre	same	ND, SD	Highly relevant due to geographic location of study	These yields were obtained under drought conditions	Perrin et al 2003
2-5.5 tons/acre	same	North Plains	Highly relevant due to geographic location of study		Walsh et al 2003

	1.6 tons/acre	Southern Iowa	Somewhat relevant. Not a study, but rather the reported yield of a farmer who grazes cows on Switchgrass until May, and then harvests in the fall.		Hipple, Duffy
Appendix A (cont.)					
	3-9 tons/acre, Overall average: 5.8 tons/acre Upland average: 6.5 tons/acre Lowland average: 5.1 tons/acre	Chickasha, OK (lowland floodplain site) and Haskell, OK (upland site)	Yields are probably too high due to southern location	The influence of topography (upland vs lowland) is important	Fuentes, Talliaferro 2002
2.5-5.5 tons/acre	Clay: avg. 5.4 tons/acre Sand: avg. 2.5 tons/acre	Brandon County, Manitoba	Relevant as sites are in the northern Great Plains		Green 2001

Appendix B. Summary of on-farm production costs for native grasses.

	UNIT	USE	PRICE	TOTAL COST
Establishment				
Tandem Disk	acre	1	$6.57	$6.57
P	lb	20	$0.30	$6.00
K	lb	30	$0.14	$4.20
Applying P & K	acre	1	$2.73	$2.73
Seed	PLS lb	10	$7.33	$73.30
No-Till Drill	acre	1	$10.16	$10.16
Roundup	gallon	0.75	$43.50	$32.63
Boom Sprayer	acre	2	$3.85	$7.70
Mowing	acre	2	$5.62	$11.24
Total Establishment Costs				$154.53
Annual Operations				
N	lb	50	$0.20	$10.00
Fertilizer spreader	acre	1	$3.81	$3.81
Total Annual Operating Costs				$13.81
Harvest				
Mowing	acre	1	$8.09	$8.09
Raking	acre	1	$3.19	$3.19
Large square bales (950 lbs)	bale	8.4	$6.03	$50.78
Staging and Loading	acre	1	$5.89	$5.89
Total Harvest Costs				$67.95

Appendix_C. Assumptions for the transportation cost model

Transportation Assumptions	
Hourly wage (for 1 driver and 1/4 loader)	$20
Waiting time to load (minutes)	45 min.
Number of additional pickups	0
Time added for an additional pickup	60 min.
Waiting time to unload (minutes)	8 min.
Diesel fuel cost ($ per gallon)	$1.5/gal.
Gas mileage of trucks (miles per gallon)	8 mpg
Non-fuel expenses for truck ($ per mile)	$0.395/mile
Driving Speed (miles per hour)	50 mph
Number of bales per truckload	36 bales
Distance conversion (constant for conversion from “crow miles” to road miles)	2.11
Tons per bale (typically .375-.5)	0.5 tons/bale
Yield per acre (tons of Switchgrass)	4 tons/acre
Acreage multiplier	1