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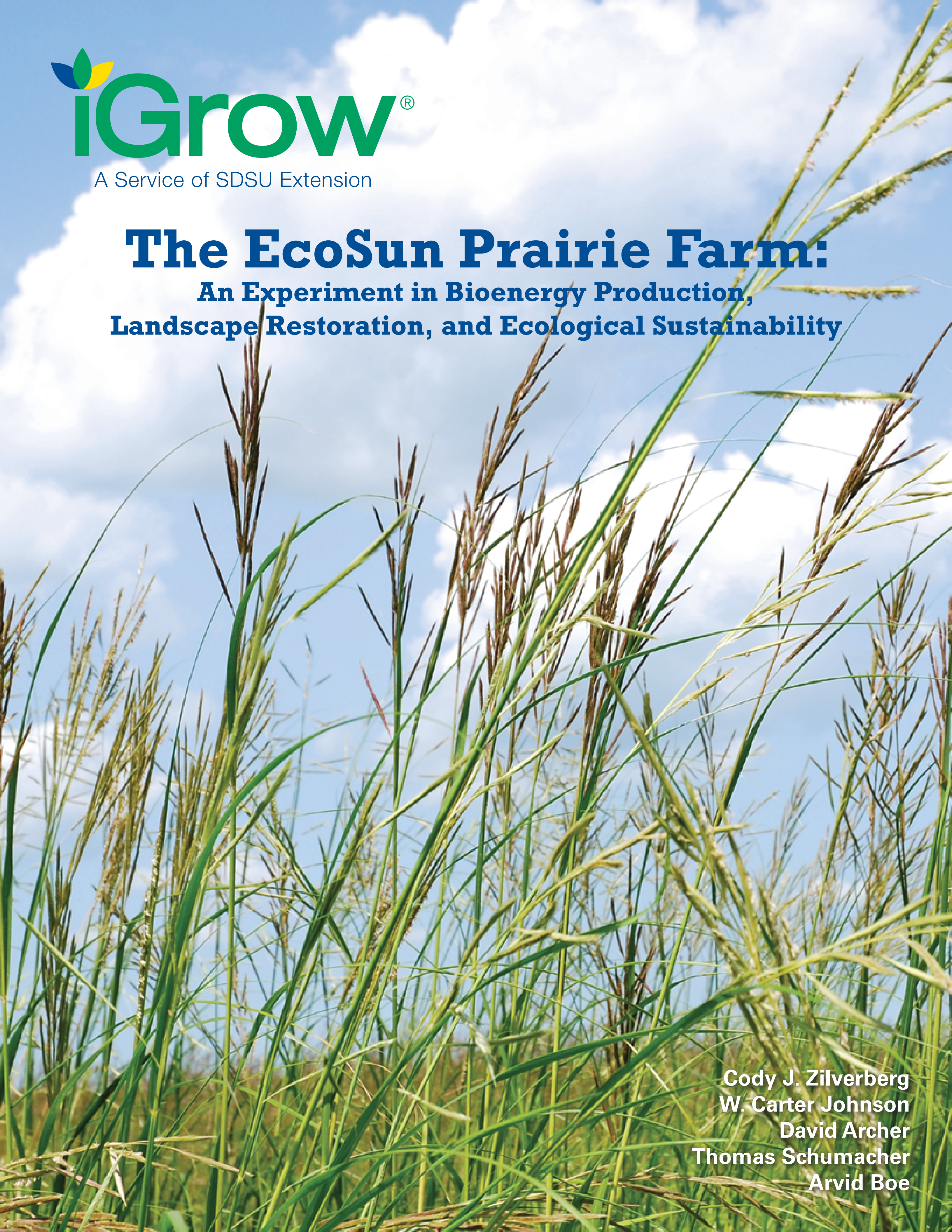
The EcoSun Prairie Farm:

An Experiment in Bioenergy Production, Landscape Restoration, and Ecological Sustainability



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CONTENTS

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ECOSUN BOARD MEMBERS: W. Carter Johnson (Chairman, 2008-present), Arvid Boe (Vice-chairman, 2008-present), Thomas Schumacher (Secretary/Treasurer, 2008-present), Scott Kronberg (2008-2013)

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PHOTOGRAPHY PROVIDED BY: Craig Novotny, W. Carter Johnson, Loretta Sorensen, Doug Backlund, Cody J. Zilverberg, Thomas Schumacher, Joseph Schumacher, and Kwan Hong Teoh.

Cover photo courtesy of Craig Novotny.

FIGURES BY: Cody J. Zilverberg

ACKNOWLEDGMENTS: Without Bill Lee's willingness to try a new way of farming on his family's land, this project may not have been possible. Craig Novotny's dedication to the philosophy and goals of the project as farm manager were invaluable. Todd Mortenson, a western South Dakota rancher, embraced the farm's goals and provided the cattle that grazed on the Prarie Farm. Special thanks to Kevin Kephart for his help in getting the Prairie Farm project off the ground. We would like to thank all of the businesses that purchased our products, including Millborn Seeds, Co-op Natural Foods, Pomegranate Market, Parker's Bistro, Cottonwood Bistro, South Dakota Agricultural Heritage Museum, and Schmidt Hay Company. Hundreds of people purchased the prairie-raised beef finished on grassland at the Prairie Farm. Tor and Tellef Johnson and Pete Carels assisted in the production of the documentary film, 'Grassroots: The Prairie Farm Story.'

Public and private agencies/organizations contributed significantly to this project. First and foremost, the North Central Regional Sun Grant Center funded several large research projects involving biofuel feedstock production and management on the Prairie Farm. The U. S. Fish and Wildlife Service assisted in restoring wetlands, funding native grass seed purchases, and fencing the exterior of the Prairie Farm. South Dakota State University loaned the project a wide range of equipment needed to establish and manage the restored grasslands and wetlands. The Nature Conservancy donated valuable native grass seed mixtures collected by combine from virgin prairie to establish high diversity plantings on the Prairie Farm.

South Dakota State University
College of Agriculture and Biological Sciences

SunGrant Initiative
North Central Center
South Dakota State University

EcoSun Prairie Farms

07-5001-2015

FOREWARD

We are excited to present, *The EcoSun Prairie Farm: An Experiment in Bioenergy Production, Landscape Restoration, and Ecological Sustainability*. This report highlights work completed at the EcoSun Prairie Farm in eastern South Dakota from 2008 to 2014. We hope it can be used as a model to those interested in diverse farming systems that are based around the use of native perennial plants. In a region primarily devoted to conventional annual agricultural crops, information gleaned from the EcoSun Prairie Farm experiment will provide producers, policy experts, and industry with farm-scale production, environmental, and economic potential of a diverse production system. The project explored and helped to quantify the capacity of native perennial plants to provide feedstocks for bioenergy and forage for livestock, develop wildlife habitat, improve soil and water quality, produce seed from native plant species, and produce high quality meat from grazing livestock.

The team involved with the EcoSun Prairie Farm experiment have documented the improvement in ecosystem services associated with proper placement and utilization of native perennial species at the farm scale. From wetlands with prairie cordgrass to fields of switchgrass monocultures and fields of simple and complex mixtures of perennial grasses, forbs, and legumes, the EcoSun Prairie Farm has helped demonstrate the importance of species selection and adaptation across a broad landscape. Research at the farm has shown the improvements in soil and water quality and wildlife habitat and reductions in greenhouse gas emissions that can be provided by diverse grassland ecosystems.

The late Aldo Leopold, wildlife biologist and conservationist, said: "We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect." Restoration of the grassland ecosystem at the EcoSun Prairie Farm serves as a model for a balanced relationship between the land and land owner. The evidence provided in this report of the rapid re-establishment of migratory waterfowl, songbirds, amphibians, and pollinator insects, which coincided with the establishment of the grassland ecosystem, is very encouraging.

We applaud the vision and efforts of those involved in the EcoSun Prairie Farm project and recognize the great value provided by this work. We hope you will enjoy and be inspired by the results of the EcoSun Prairie Farm experiment.

Barry H. Dunn
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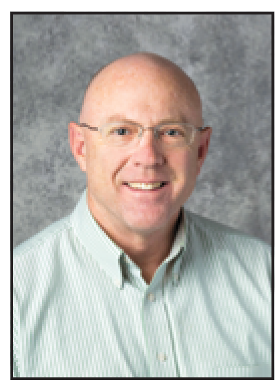

Vance Owens
Director of North Central Regional
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EXECUTIVE SUMMARY

In 2008, the non-profit corporation, EcoSun Prairie Farms (hereafter EcoSun), began establishing mixtures and monocultures of native prairie species in eastern South Dakota on a section of land (hereafter Prairie Farm) that had been conventionally farmed with annual crops for more than a century. The purpose of EcoSun's farm-scale experiment was to demonstrate that farming native perennial species was an economically viable option for landowners in eastern South Dakota and the surrounding region. Revenue would be generated by selling biomass as hay and biofuel feedstock, by grazing commercial livestock, and by selling native plant seed. It was anticipated that the conversion from conventional annual crops to native perennials would also greatly increase the provision of ecosystem services, including cleaner water, improved wildlife habitat, and reduced soil erosion. During the farm's operating years, from 2008 to 2014, numerous experiments were conducted, ranging from the landscape-scale down to plots of 0.5 feet^2. Most of this research was funded by the Sun Grant Initiative through the North Central Regional Sun Grant Center, based at South Dakota State University in Brookings, South Dakota.

The Prairie Farm's topography was typical of the Prairie Pothole region, characterized by rolling hills and numerous wetlands that provide much-needed habitat for migratory waterfowl and upland bird populations. In the distant past, nearly all of the wetlands were drained by ditches to facilitate the production of grain crops; consequently, one of the first activities undertaken was to plug ditches and create berms to restore surface water conditions. Thirty-five selected native tallgrass prairie plant species and bulk seed from a remnant prairie that contained about 200 species were planted on the farm. Planted species included grasses, sedges, and forbs, but after establishment generally just a few species, primarily grasses, dominated the vegetation. In the uplands, these were switchgrass, big bluestem, and Indiangrass. Switchgrass was also planted in monocultures for seed production in addition to its inclusion in several seed mixtures. Within two to three years after establishment, big bluestem tended to dominate in the mixed plantings.

Establishment of upland native plant communities ranging in size from 10 to 113 acres was highly successful. Up to 125 acres were established annually for the first four years. As is commonly recommended, we found raising soybeans in the year before planting perennial grasses provided a good seedbed for establishment. We applied preplant herbicides and seeded with a grass drill between April and mid-June at a rate of 9 lb PLS (pure live seed)/acre for the mixtures. After emergence we mowed 2 to 3 times during the establishment year to subdue the growth of annual weeds. In subsequent years, weeds were controlled by a combination of herbicide, mowing, and prescribed burning.

Because of their botanical simplicity and uniformity, switchgrass monocultures were the easiest fields to manage. In addition, the seed raised in these fields provided some of the highest net income/acre on the farm. Switchgrass also yielded consistently high levels of biomass across a range of topographic positions, averaging 5.3 tons/acre (range from 3.6 to 6.4) from 2009 to 2014 when cut at ground level shortly after killing frosts in autumn. In contrast, mixtures dominated by big bluestem yielded less (3.6 tons/acre; range from 2.5 to 5.2), but of course provided more biodiversity. One benefit of diversity was that mixtures including cool season grasses provided grazeable forage earlier in the growing season than mixtures composed of only warm season grasses, such as switchgrass and big bluestem. Unfortunately, their phenological diversity also made them more difficult to manage for grazing and confined use of herbicides to narrower time periods.

Prairie cordgrass was the most commonly planted species in wetlands. We used several establishment techniques. One successful technique was drilling seed, similar to the method used for uplands. An alternative was to use dibbles to hand-transplant greenhouse-started seedlings on a grid with 5-foot inter-plant spacings. This method was more successful than a grass drill in the deepest parts of wetlands. When the soil was dry, a tree planter was also found to be successful to efficiently transplant, being much less time consuming than transplanting by hand. Although planted as monocultures, cordgrass stands commonly contained understory vegetation that added diversity. Biomass yields of cordgrass in the wetlands (4.6 tons/acre) were similar to switchgrass in the uplands. Like switchgrass, cordgrass provided valuable seed, but cordgrass seed yields were more variable than switchgrass. Burning cordgrass residue in the spring tended to increase seed production. Other wetland species were planted and allowed to revegetate the farm's wetlands, but only one, prairie wedgegrass, contributed significantly to the farm's revenue, by providing high-value commercial seed for wetland restoration projects.

At the onset, the Prairie Farm's anticipated sources of revenue were seed, biomass, and livestock. For the duration of the project, seed sales were dominated by switchgrass and prairie cordgrass. The market for selling ligno-cellulosic feedstock to a biofuel refinery did not develop during the farm's operation (2008 to 2014) as anticipated—therefore, biomass was harvested and marketed as hay. Some conventionally-harvested spring and summer hay was produced, but most hay was harvested at maturity after senescence during autumn, using methods (i.e., large round bales) similar to those that would be used to produce biofuel feedstock. We received grazing fees for custom grazing of beef cattle, and beef (19,000 pounds) from a select number of animals was marketed under EcoSun's "prairie-raised" brand. A benefit of this research was its demonstration of utilizing existing markets for ligno-cellulosic feedstock that could precede, complement, or follow the sale of the same materials to a biofuel market, should such a market develop. These alternative markets could be important to producers who are uncertain about "betting the farm" by establishing perennial crops to sell to an immature and uncertain biofuel market.

Models of soil erosion showed that parts of the farm's landscape had suffered annual erosion rates greater than 30 tons of soil/acre/year when it was producing grain crops, due to water and tillage. However, these erosion rates dropped to near zero after perennial grass was established. During the farm's operation, we observed soil erosion on tilled fields but not on fields with established perennial grasses. After a few years in grassland, measures of soil quality began to improve, but were still considerably lower than a nearby remnant prairie that had never been tilled. Although not measured on our farm, other research has shown that re-establishing perennial vegetation dramatically changes a farm's water budget. Less water runs off to reduce stream and river flooding downstream and more water percolates deeper into soil to supply plant growth and to recharge local aquifers.

As many as 100 species of birds, including three species of geese, rested and foraged on the Prairie Farm during both spring and autumn migration. Grassland birds that are in severe decline throughout the Great Plains because of the loss of grassland habitat became abundant on the Prairie Farm, including flocks of Bobolinks numbering from 50 to 100 birds. Mallard and Blue-winged Teal ducks commonly nested in the restored grassland. Obligate wetland birds were also observed nesting, including the Sora and Virginia Rail, Sedge Wren, American Bittern, and Black-crowned Night Heron. The Chorus Frog, Spring Peeper Frog, Leopard Frog, and American Toad rapidly colonized restored wetlands, dramatically changing the farm's spring soundscape.

A life cycle energy analysis showed that most energy use and greenhouse gas emissions were the result of direct fuel use (gasoline and diesel), but that fertilizer was a large energy input in the year that it was applied. The energy of the biomass produced was 32 to 62 times greater (based on the lower heating value) than the amount of energy required to produce the biomass, but additional energy would be required for transportation from the farm and conversion of the biomass into fuel products.

The farm's scholarly and outreach activities were many, including production of a documentary film, education of 2 post-doctoral researchers, 6 graduate students, 9 undergraduate student workers, more than 26 farm tours, 6 peer-reviewed publications, 2 book chapters, 14 other publications, 44 presentations, 4 posters, and 4 final reports.

The Prairie Farm experiment demonstrated that diverse mixtures of native grassland species can be successfully established, managed, harvested, and marketed on former cropland in the northern Tallgrass Prairie region. Once established, the farm produced income similar to the median household income in South Dakota. However, income from grassland products was less than could have been received from renting the land for conventional crop farming. Improved marketing and more focus on specialty enterprises with high returns per acre could have increased revenue. However, economic feasability is a common problem encountered in ecosystem restoration; a farmer converting formerly tilled land to grassland is not financially compensated for the many new services (such as water purification, soil retention, groundwater recharge, pollinators, climate protection, and aestetics) his management change provides to the public. Lack of compensation for providing ecosystem services limits the profitability of restored grassland and hence their adoption by landowners.

Despite this challenge, the economic value of ecosystem services is starting to be acknowledged. For instance, the city of New York chose to improve its water quality by restoring the watershed of the Catskill Mountains, which was cheaper than building a water filtration plant. Closer to home, the city of Des Moines, IA has recently filed a law suit against upstream drainage districts to recover the costs the city incurred to remove nitrates from river water. The U.S. government currently subsidizes the production of farm program crops. If some of those acres were converted to perennial grassland, subsidies could be used to pay for the ecosystem services provided by the grassland without increasing the cost to taxpayers. Loosening of restrictions to allow more frequent harvesting of Conservation Reserve Program lands could also be a model for simultaneously providing agricultural goods and ecosystem services with public financial support.

In conclusion, this seven-year experiment has generated considerable quantitative data on the production, management, and marketing of biomass feedstock to inform a nascent cellulosic biofuel industry, should one develop in the near future. To encourage widespread adoption of the Prairie Farm model, the model must work for both the farmer and the public. Several ways this might happen are: 1) the grassland farmer receives appropriate compensation from the public for the ecosystem services provided, 2) the prices of common grassland products (e.g., seed, hay, beef, biofuel feedstock) in the marketplace improve relative to commodity crops, and/or 3) governments or non-profit corporations subsidize grassland farms and commodity crops similarly, rather than favoring the production of commodity crops. Should the value of commercial grassland farms become more widely recognized and monetized, adoption of Prairie Farm practices will become more likely in farm country throughout the northern Great Plains and Midwest.

Chapter 1

EcoSun Prairie Farms



EcoSun board members, Arvid Boe, Carter Johnson, and Thomas Schumacher.

Purple prairie clover on the Prairie Farm.

THE COMPANY AND ITS MISSION

EcoSun Prairie Farms Inc. is a South Dakota non-profit corporation formed in April, 2007. It received tax-exempt status and classification as a public charity from the Internal Revenue Service (IRS) in February, 2008. The Board of Directors has consisted of current and former scientists and educators from South Dakota State University committed to investigating alternatives to traditional agricultural practices that may be more ecologically and economically sustainable.

EcoSun board of directors, past and present
W. Carter Johnson (Chairman, 2008-present)
Arvid Boe (Vice-Chairman, 2008-present)
Thomas Schumacher (Secretary/Treasurer, 2008-present)
Scott Kronberg (2008-2013)

EcoSun launched a "Prairie Farm" project in autumn 2007 on a leased 650-acre farm in Moody County, about 25 miles south of Brookings. The main thrust of the project, completed in 2014, was to demonstrate how to make a living from retired cropland that was planted back to native grassland species while protecting and enhancing the environment. The Prairie Farm project promoted the benefits of a working landscape by emphasizing the potential of multi-functional agriculture, defined as the joint production of a standard commodity (e.g., food) together with ecological services such as clean water, healthy soil, climate protection, and biodiversity.

The dominant regional cropping system is the corn-soybean rotation, which uses annual crops and is input-intensive. In contrast, EcoSun sought to balance provision of ecosystem services with economic stability by developing a low input, perennial crop farming system with diverse income streams, including the sale of forage, seed from native wetland and upland prairie plants, feedstock for cellulosic biofuels, prairie-raised beef, carbon credits, recreation (including fee hunting), and grants for farm-scale research. Expected environmental benefits of the project were: improved surface and ground water quality, restoration of several dozen previously drained wetlands, reduced soil erosion, increased soil carbon, and abundant wildlife, among others.

During the first few years of the project, approximately 100 acres/year of retired cropland were planted to various mixtures of native grasses and forbs (flowers), for a total of ~370 acres. Economics were considered when deciding which species to plant. For example, consumers of seed typically prefer to buy single species and mix them in desired proportions. Hence, about 65 acres were planted to three varieties (Sunburst, Summer, Nebraska 28) of switchgrass monoculture. About 100 acres were planted with a high diversity mix that included both cool season and warm season native grasses. Approximately 60 acres were snow-seeded using seed combine-harvested from Sioux Prairie, a high diversity (220 species) virgin prairie owned by The Nature Conservancy and located just 2 miles from the Prairie Farm. The dominant species in the mixed-species plantings was big bluestem, a high-quality forage common to the Tallgrass Prairie. About 80 acres of former CRP were only partly renovated. The balance of the farm (~190 acres) which included the farmstead, a semi-permanent wetland, exotic grass pasture, and 64 acres of cropland was not converted to native prairie species.

Wetlands and other subirrigated land are particularly troublesome for conventional farming because their soils are often too wet to plant, and if planting is successful, the subsequent crop may fail due to flooding after emergence. In contrast, EcoSun viewed wetlands as particularly valuable assets that could potentially produce a valuable seed crop, a hay crop, and some of the best wildlife habitat on the farm. Thus, shallow wetlands and other subirrigated land that had been drained for row crop production were restored, primarily to produce prairie cordgrass and several native associates, such as sedges.

The project's results, both economic and ecological, form the basis of the following report.

ECOSUN AND THE NORTH CENTRAL REGIONAL SUN GRANT CENTER

The North Central Regional Sun Grant Center, based at South Dakota State University in Brookings, South Dakota, and the EcoSun corporation, also based in Brookings, South Dakota, had a very productive relationship from the time EcoSun began operations in 2007. It became clear that knowledge of biofuel feedstock production and economics at the whole-farm scale, which was a programmatic goal of the Prairie Farm project, would match the research needs of the Sun Grant Center. As such, the Sun Grant Center funded EcoSun to conduct biofuel research to: (1) develop methods to renovate degraded CRP into productive swards of warm season grasses for use as biofuel feedstock, (2) identify factors that control grass production across heterogeneous landscapes, including topographic position, seeding rate, species composition, and management; (3) document changes in environmental quality resulting from the conversion of tilled fields and wetlands to native species with high biofuel potential; (4) conduct field experiments to determine if the biodiversity of switchgrass plantings can be increased without significant loss of total stand biomass; and (5) complete an integrated economic analysis of the potential profitability and sustainability of a grass-based biofuel farm, including the costs of conversion and restoration.

The North Central Sun Grant Center, through a grant provided by the US Department of Energy Bioenergy Technologies Office under award number DE-FG36-08GO88073, funded three EcoSun proposals to fulfill research objectives listed above. The funded projects were:

1. Landscape Scale Lignocellulosic Biomass Production, Economics, and Environmental Quality (2008 to 2011)
2. Biofuel Feedstock Crops on Sub-Irrigated Lowlands (2010 to 2012)
3. Enhancing Biodiversity of Switchgrass Biofuel Feedstock Plantings (2012 to 2015)

Funding was also provided by a Conservation Innovation Grant from the Natural Resource Conservation Service. Briefly, the majority of the funding was used to support 6 SDSU graduate student projects and 2 post-doctoral associates, travel between SDSU and the Prairie Farm and for presentations, and research supplies and equipment. Output from the project included numerous presentations, including farm tours; graduate student theses; peer-reviewed publications; quarterly and final reports to the Sun Grant Center; and numerous press accounts of the project. Research results and findings are detailed in the body of this report.

Chapter 2

EcoSun Prairie Farm Landscape and Surrounding Farmland

A large semi-permanent wetland at the top of the photo has retained water into autumn, but two temporary wetlands planted to prairie cordgrass, in the center of the photo, have long-since dried up.

The EcoSun Prairie Farm (44.029 latitude, -96.850 longitude) was located near Colman, SD, in the North American Tallgrass Prairie and the Prairie Pothole region. This region has global importance for wildlife because its abundant wetlands support migrating waterfowl; its grasslands provide nesting and resting habitat for bird species that overwinter as far away as South America. It also supports many other species of conservation interest, such as the Dakota Skipper butterfly. The region's natural areas also provide habitat for upland game, including Whitetail deer and Chinese ringneck pheasants.

Most of the Tallgrass Prairie has been converted to the production of grain crops, so that less than 4% of the original habitat remained in the 1990's (Samson and Knopf, 1994). South Dakota has retained a greater percentage of its Tallgrass Prairie than neighboring Iowa, but high grain prices from 2010 to 2014, combined with the expiration of many CRP contracts, continue to reduce the amount of grassland remaining (Wright and Wimberly, 2013; Johnston, 2013). Continued conversion of grassland to annual grain production contributes to the dwindling acreage of high quality wildlife habitat, deteriorates soils, and alters the region's hydrology.

Patchwork of fields and wetlands on the EcoSun Prairie Farm. Photo courtesy of Craig Novotny.

The farm is part of the rolling plains typical of the region. When EcoSun assumed management, the farm contained approximately 40 semi-permanent, temporary, and seasonal wetlands, most of which had been drained by ditches to facilitate annual crop production. The farm had been cultivated for the past century (Olson et al., 2014), most recently as a corn-soybean rotation. Silty clay loams were the predominant soils, two-thirds of which were considered "prime" farmland by NRCS designation (Appendix Figure A1). Mean annual precipitation (1981 to 2010) at nearby Flandreau, SD is 27 inches, mean minimum temperature 33°F, and mean maximum temperature 54°F.

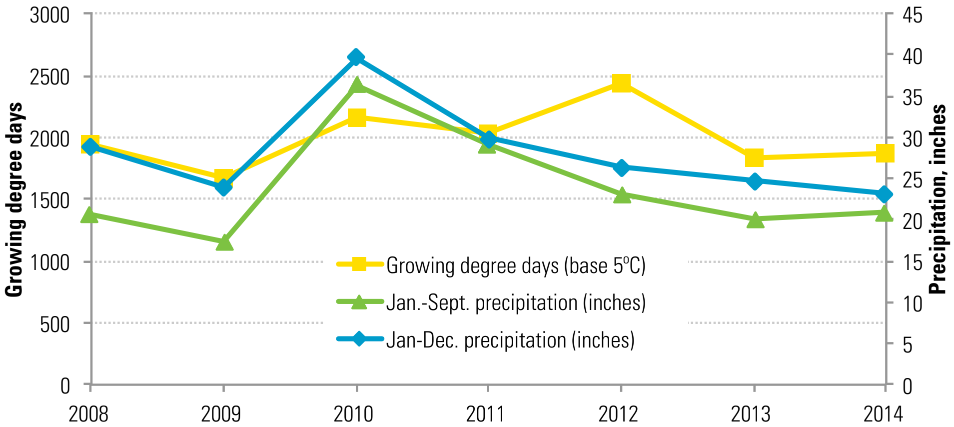


Figure 1. Growing degree days through September 30 with a base temperature of 5°C (32°F) during the farm's operation, as well as precipitation from January 1 to September 30 or December 31. Weather records from Flandreau, SD.

Chapter 3

Establishment: Selecting Species While Considering Yield, Diversity, and Site Conditions

The cup plant flower.

The importance of successful establishment cannot be overemphasized. Poor establishment, whether due to adverse weather conditions or corner-cutting, is expensive due to the need to replant, the increased need for weed management, and reduced revenue due to low and/or delayed yields in future years. In accordance with EcoSun's philosophy of diversifying enterprises and techniques, we used a variety of establishment strategies.

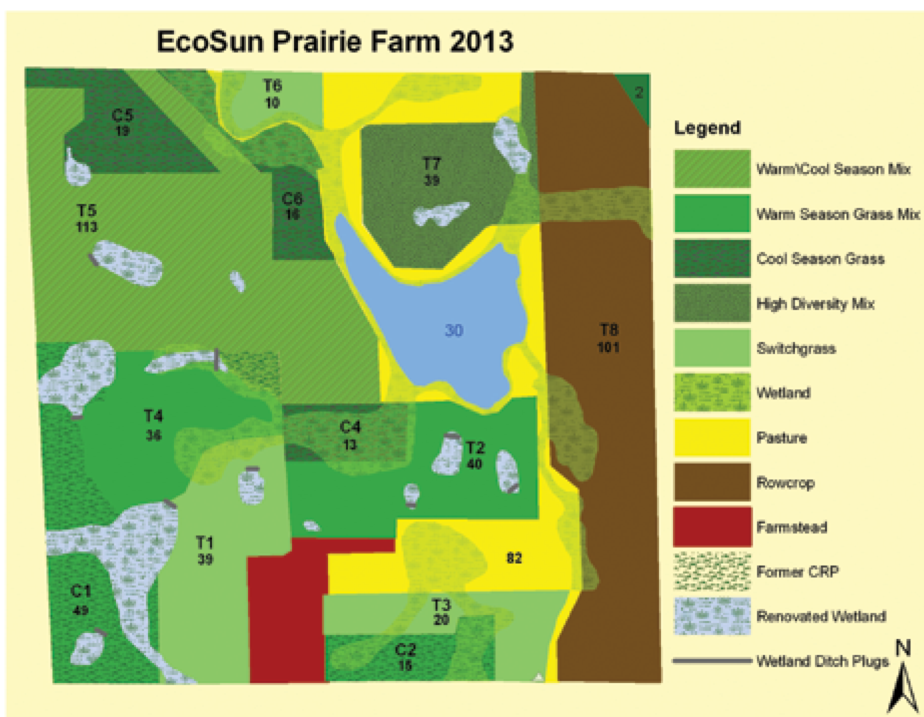
The starting point for establishment was recognizing that the farm contained heterogeneous soils and topography, and that establishment of many prairie species would succeed or fail depending upon our ability to place them in the correct locations in the landscape. In practice, this meant that areas previously farmed as a single field were divided into upland or wetland areas, primarily determined by depth to water table.

UPLAND COMMUNITIES

Renovation of Conservation Reserve Program (CRP) fields

Contracts on approximately 140 acres of CRP on the Prairie Farm expired during year 3 of the project. After decades in the program, these fields were dominated by invasive plants rather than the warm season grasses initially planted. The primary invasives were smooth brome (*Bromus inermis*), reed canary grass (*Phalaris arundinacea*), quack grass (*Elymus repens*), Canada thistle (*Cirsium arvense*), and sweet clover (*Melilotus spp.*). Also, pocket gophers (*Geomys bursarius*) had built many soil mounds, making vehicular field work difficult or impossible. In advance of the expiration date, EcoSun was given permission from the NRCS to engage in studies to convert fields dominated by invasive plants to warm season grasses more appropriate as biofuel feedstock.

To allow machinery to spray and harvest the crop, pocket gophers were removed by a combination of trapping and use of a rodenator (a device that ignites gasses within a burrow to kill the pocket gopher), and mounds were removed by disking with a conventional tractor. The largest field converted by this technique was C1 (see map), which was 49 acres in size.



Field names on the Prairie Farm begin with a letter indicating they were recently in the Conservation Reserve Program ("C") or were tilled ("T") in a corn-soybean rotation. The yellow "pasture" was dominated by exotic cool season grasses. Numbers below each field name give the size of the field, in acres. Figure courtesy of Craig Novotny.

Conversion of the plant community was accomplished using the following methods. We sprayed with glyphosate in the spring when the cool season grass was actively growing. Once the field was brown and dry, it was burned. Disking followed to flatten the field. We disked a second time in the autumn and a third time in the following spring to destroy root clods. We sprayed again in the autumn and the following spring to kill regrowth. The field was drilled with warm season grasses only. In one case, we cultipacked the field before drilling; we recommend this for future plantings. After planting, the CRP fields were treated with herbicide and mowed as were the other production fields not in the CRP program. When CRP fields reached the end of their contracts they were rented by EcoSun.

Revegetating fields previously planted to annual crops

Corn residue prevents good seed-to-soil contact and rooted corn stalks prevent use of grass drills. Thus, for fields in a corn-soybean rotation, we planted in the year following soybean production. We typically applied a pre-plant herbicide, such as Plateau[1] (imazapic). Glyphosate was sometimes applied in the early spring to kill weeds that had already germinated. All upland fields were planted using a 10.5 foot-wide Truax grass drill (Truax Company; New Hope, MN). Upland fields were planted at a seeding rate of 9 pounds PLS (pure live seed)/acre based on recommendations from experts at South Dakota State University. However, researcher Chang Oh Hong also conducted an experiment on the farm to determine the optimum seeding rate for 'Sunburst' switchgrass. Sunburst was planted at three landscape positions (shoulder, midslope, and footslope) and three seeding rates (5, 10, or 15 pounds PLS/acre) in 2008. The plots were sampled annually from 2009 to 2011, and he found no difference in autumn biomass among seeding rates. Thus, under *optimum* conditions, the lower seeding rate (5 pounds PLS/acre) was adequate, but higher seeding rates (9 to 10 pounds PLS/acre) may be needed when the seedbed is suboptimal.

Seeding in April is preferred, but can be delayed until mid-June. At EcoSun, the earliest planting date for any of our fields occurred on April 9th, and the latest occurred on June 17th. Later planting dates were usually caused by lack of equipment availability or heavy rain events. We did not use a cultipacker, although cultipackers are often recommended for good seed-to-soil

[1] Inclusion of information about Milestone, Paramount, Plateau and trade names of other products used does not mean that EcoSun promotes the products.

contact. In two instances, we reseeded areas in the second year due to poor establishment. This included field T3, where 5 acres of switchgrass were re-drilled in the following spring. In field T6, a small area was broadcast with switchgrass seed during the first winter after planting. Overall, our seeding was very successful, as over 300 acres established well with a single seeding.

An exceptional case was the establishment of T7, the 'Sioux Prairie' field. This field was snow-seeded on December 1st with seed harvested from the Nature Conservancy's 'Sioux Prairie' property, just 2 miles from our farm. Snow-seeding is done by broadcasting seed over snow. The snow layer makes it possible to see how much seed has been scattered and the extent of coverage. The freeze-thaw process "plants" the seed in the soil surface. Because this seed was harvested and planted in bulk, the PLS seeding rate is not known.

In the first 1 to 2 years of establishment, the growth of annual weeds, such as water hemp (*Amaranthus* spp.), outpaced the growth of native perennial grasses. EcoSun employed a combination of mowing and herbicides to control these weeds. All fields were mowed at least once in the establishment year to reduce weed height, open up the canopy, and allow sunlight to reach the grass seedlings. Only in field T5, which contained warm season grasses, cool season grasses, and forbs, was post-planting herbicide used in the establishment year. In that case, we spot-sprayed thistles with Milestone (aminopyralid) and mowed twice.

In the year after seeding switchgrass fields, Milestone and sometimes Paramount (quinclorac) were applied to the entire field. In mixed-species fields, Milestone or glyphosate was used to spot-spray in the year following seeding. All mixed-species fields were also spot-mowed to reduce weed pressure and prevent thistles from producing seed.

Black-eyed susan is a native, ruderal species, one that establishes quickly. Included in the seed mix for T2, it was initially very common but its frequency declined over time.

Recommended method of establishment for uplands			
	Year 0	Year 1	Year 2
Switchgrass monocultures or mixtures of prairie species	**Raise soybeans**	**Preplant:** Apply Plateau & glyphosate. **Seeding date:** April to mid-June. **Seeding rate:** 5 to 9 lb PLS/acre. **Post-seeding:** Mow 2-3 times above the height of the grass to control tall weeds.	**Reseed** areas of field that did not establish well, if necessary. **Spot-spray** with Milestone as needed to control weeds.

Selecting species for upland plant communities

EcoSun experimented with mixtures and monocultures of prairie plants at both field (up to 113 acres) and small plot (~1 yard^2) scales. The reason for this was twofold: 1) to make comparisons among different mixture and monoculture options and, 2) to diversify EcoSun's income streams to reduce financial risk. Diversification of species mixtures helped EcoSun balance its goals of profitability and provision of ecosystem services.

Production-scale fields

We planted three fields (T1, T3, and T6; see map to locate fields by name), totaling 69 acres, to switchgrass monocultures. Four others were planted to species mixtures, including: 1) a simple mixture of 5 warm season grasses (T4; 40 acres), 2) a mixture of 13 warm season grasses and forbs (T2; 40 acres), 3) a mixture of 24 warm season grasses, cool season grasses, and forbs (T5; 113 acres), and 4) bulk seed harvested from a nearby virgin prairie (T7; 38 acres; Appendix Table A1). Thus, our upland plantings ranged from monocultures to high-diversity plantings. We measured performance of these fields in two ways. Each autumn, we hand-harvested multiple areas (5.4 feet^2 each, except for cordgrass which was 10.8 feet^2) of most fields at ground-level using a rice-knife. We report all yields on a dry-matter basis. Many of the fields were also harvested by farm-scale haying machinery. We counted the number of bales produced by each field and multiplied by the average bale weight to determine the harvested mass. Bale weights are given on an "as-is" basis. Large round bales typically contain 80-85% dry matter, but ours were often higher in dry matter because they were baled after a frost. In 2012, bales tested at

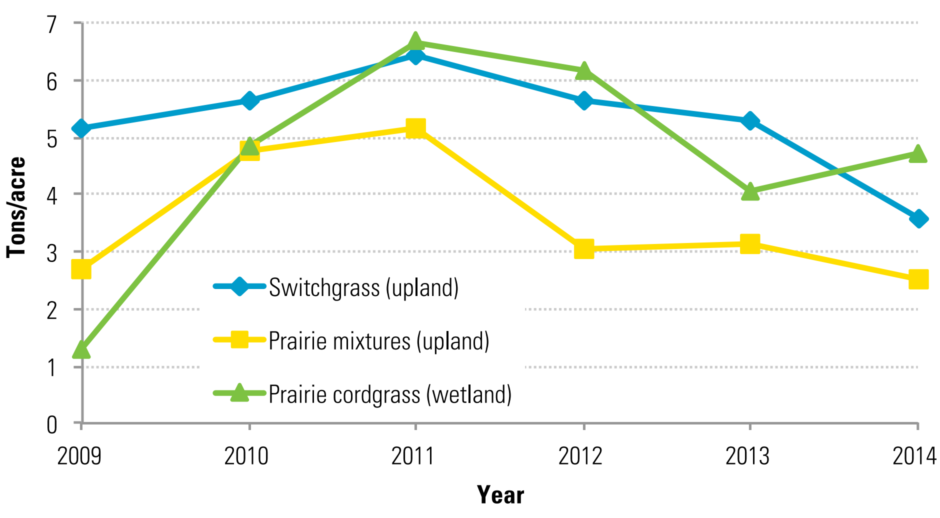


Figure 2. Yield of switchgrass monocultures, mixtures of upland prairie species, and a prairie cordgrass-dominated wetland when harvested by hand at ground level. Data were from production-scale fields. Seeding-year data was excluded. Data were 2009 to 2012 were previously published in Zilverberg et al. (2014b)

89.5% dry matter. Dry matter data are not available for other years. Yield data for some fields were not available in some years because they were grazed or were harvested for seed before sampling.

The results of hand-sampling revealed that switchgrass monocultures outproduced diverse mixtures in every year after establishment, although the difference between the two was sometimes small (Fig. 1). Prairie cordgrass, which will be discussed in more detail in the wetland plants section, yielded similarly to switchgrass. All three vegetation types reached peak biomass production in 2011, which was 1 to 3 years after they had been established, depending on the field. This also corresponded with the wettest consecutive years (2010 to 2011) during the experiment, but other factors may also have contributed.

Replicated experiments: Switchgrass vs. big bluestem mixtures

A foundational principle of the EcoSun experiment was recognizing that species have topographic optima where they survive and grow the best, and strategically utilizing that knowledge to increase biomass yield and diversity. Therefore, we conducted a number of experiments to determine the impact of topographic position on biomass yield and interspecific competition.

Two of these replicated experiments compared yield of 'Sunburst' switchgrass monocultures planted at 10 lb PLS/acre to mixtures dominated by big bluestem planted at 9 lb PLS/acre. The seed mixture was the same as that used in field T2. Both experiments were planted in 2008 with three landscape positions: shoulder, midslope, and footslope. There were several important differences between the two experiments. The soils from experiment 1 were Wentworth-Egan silty clay loams with a crop productivity index of 86 and normal range production of 3800 pounds/acre (Soil Survey Staff, 2015). The shoulder and midslopes of experiment 2 included Wentworth-Egan silty clay loams as well as the Dempster-Talmo complex, which has a crop productivity index of 29 and range production of 3300 pounds/acre. At the footslope, experiment 2 included Worthing and Baltic soils. The Baltic silty clay loam has a crop productivity index of 34 and a range productivity of 6700 pounds/acre. Both experiments were harvested at a 4-inch stubble height, but experiment 1 was harvested by hand whereas experiment 2 was harvested by a sickle-bar mower. Finally, we observed that experiment 1 achieved greater initial plant density than experiment 2. Results through 2012 were reported by Zilverberg et

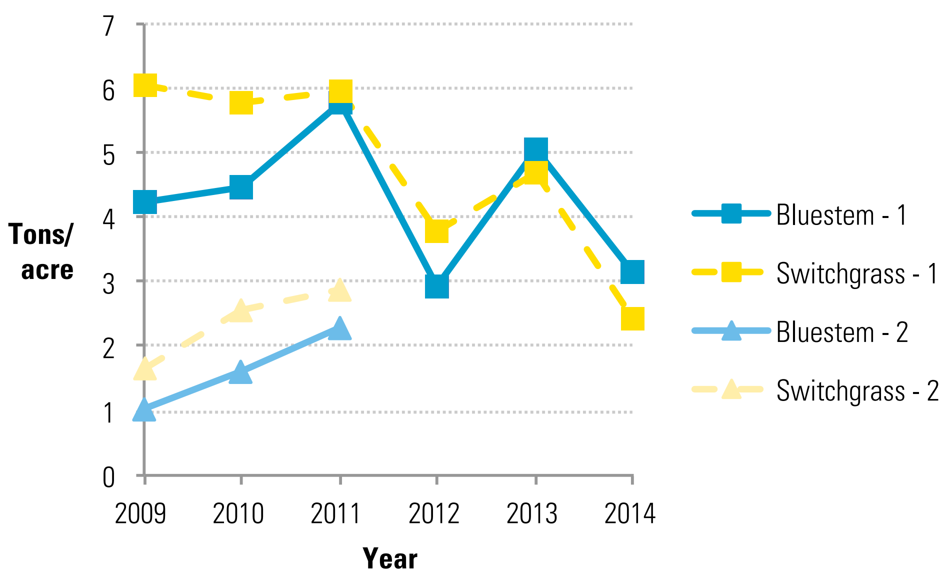


Figure 3. Mean yield of Sunburst switchgrass monocultures vs. mixtures dominated by big bluestem from replicated experiments 1 and 2. Both were harvested at a 4-inch stubble height. Seeding-year data were excluded. Data from 2009 to 2012 were previously published in Zilverberg et al. (2014b)

al. (2014b). Here, we review those results and update them with data collected through 2014.

In both experiments, yield of Sunburst switchgrass initially outyielded the mixtures. With time, the mixtures became heavily dominated by big bluestem (83% of canopy cover) in experiment 1, in part due to the broadleaf community being inadvertantly damaged by herbicide. At the same time, the mixtures improved relative to switchgrass, although yields of both species declined from 2011 to 2014. It is not clear if the mixture's improved performance over time, relative to switchgrass, was because of the decrease in diversity or in spite of it. In these experiments, there was no change in the relative dominance of one treatment over the other at different landscape positions, probably because both are adapted to similar soil conditions in natural stands and because our landscape positions did not include sites that were extremely dry or wet.

Replicated experiment: Switchgrass monoculture vs. switchgrass-prairie cordgrass mixture

In selected plots of experiment 2, described above, we transplanted plugs of prairie cordgrass into the switchgrass monoculture every 5 feet along the elevational gradient in 2008 and allowed prairie cordgrass to spread vegetatively into the switchgrass stands. Then, in 2013 and 2014, we used a sickle-bar mower to cut monoculture switchgrass plots and adjacent switchgrass-cordgrass mixtures at a 4-inch stubble height along the length of the elevational gradient. We found that yield of both treatments decreased moving upslope. Mean yield of switchgrass along the elevational gradient was 2.2 tons/acre for the two years, which was slightly lower than yields from the same plots when measured in 2010 and 2011 as part of experiment 2.

At the lowest elevations, cordgrass and switchgrass were found in approximately equal proportions when mixed together. However, as we moved upslope, switchgrass came to dominate the plots. This result is consistent with observations of natural stands of Tallgrass Prairie, where cordgrass is typically more abundant in lowlands than switchgrass. Even the lowest elevations of this experiment were probably more suited to switchgrass than cordgrass. Had the experiment extended into water-logged soils further downslope, cordgrass would probably have come to dominate the plots.

A row of prairie cordgrass plants after transplanting into a plot that had been seeded to switchgrass.

Replicated experiments: Switchgrass monoculture vs. strategic mixtures and monocultures

Two experiments were conducted to compare the performance of 'Sunburst' switchgrass at different landscape positions against the performance of alternative monocultures and mixtures, selected for their adaptation to specific topographic positions. Mixtures included 2 to 4 species. Both were small plot experiments where biomass was harvested by hand in autumn.

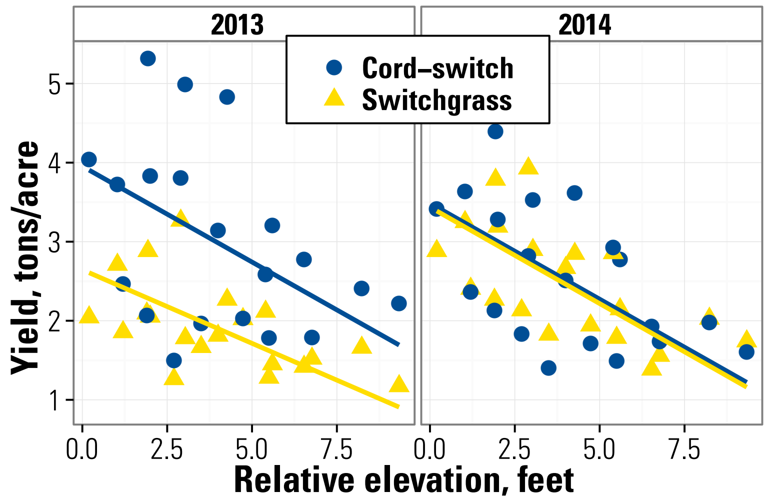


Figure 4. Yield of switchgrass monocultures vs. mixtures of prairie cordgrass and switchgrass in 2013 and 2014. Yield of both treatments decreased as one moved upslope (to the right in these graphs).

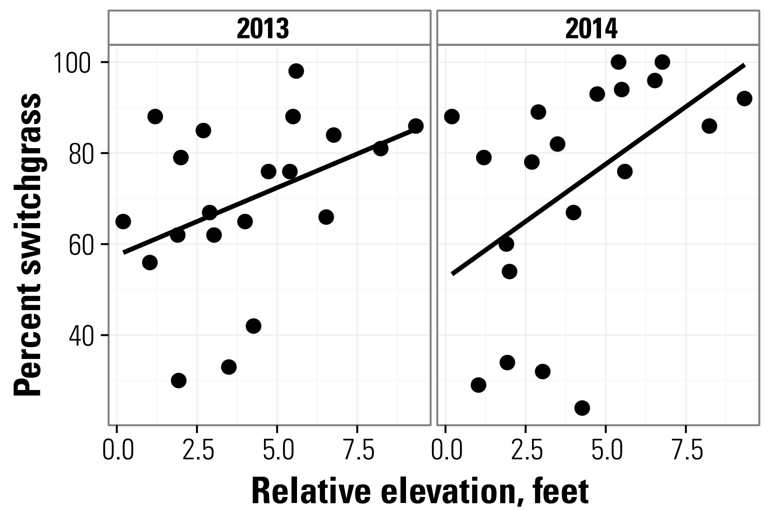


Figure 5. As elevation increased (moving to the right in these graphs), mixtures of prairie cordgrass and switchgrass became dominated by switchgrass.

We found that switchgrass biomass yield varied little, regardless of whether it was planted at the shoulder, midslope, or footslope. We also found that the yield of the highest-yielding alternative species, whether in monoculture or mixed with switchgrass and other species, equaled or exceeded the yield of switchgrass monocultures at all landscape positions. Therefore, we concluded that field-scale biomass and biodiversity could be simultaneously enhanced by planting a number of topographically targeted species and species-mixtures, rather than a switchgrass monoculture. Details of these experiments were reported by Zilverberg et al. (2016) and Teoh (2015).

Species-sorting in production fields planted to a uniform seed mixture

In nature, the seeds of a particular species may be distributed across a heterogeneous landscape and deposited in a wide variety of sites. Some of these sites will be unsuitable for the species. In other sites, the species will grow and survive before being outcompeted by other, better-adapted species. But, in certain locations, the species will thrive. We were determined to discover how this process of competition among species would progress when a topographically heterogeneous field was planted to a mixture of regionally-adapted but commercially available grass and forb seeds. Would the field's mixture of species remain in the same proportions as the original seeding mix? Or would certain species dominate different parts of the field, based on soil and other site differences?

To answer this question, we conducted an experiment in two of the previously described fields (T2 and T5) planted to diverse mixtures of 13 or 24 species. Soils were in the Egan-Ethan complex or were Wentworth-Egan silty clay loams. In each field, we placed grazing exclosures on two slopes that maximized elevational change over a relatively short distance. The slopes were confined to upland plant communities. Near the time of peak biomass, usually in August, we measured canopy cover of individual species within 11-feet^2 quadrats along each transect. In autumn, we measured biomass. We also measured 1) local slope, which was the elevation change from one plot to the next, and 2) relative elevation, which was the elevation above the lowest point in each transect.

Field T5 produced abundant wildflowers in 2012. Purple prairie clover, white prairie clover, and upright prairie coneflower are seen in the foreground. The cream-colored flowers of Canada milkvetch in the background were preferentially grazed by EcoSun's heifers. Photo courtesy of Craig Novotny.

Mowing a transect in a bluestem-dominated field. The cut hay was collected by hand, sorted by species, and weighed.

We found that species-sorting occurred in both fields. That is to say, although entire fields were planted to the same seed mix regardless of topography, certain species increased or decreased their dominance depending on local slope. This was especially true in field T2, where big bluestem was replaced by Indiangrass and little bluestem on steeper slopes. In T5, the legumes purple prairie clover and white prairie clover made up a small percentage of canopy cover but were nearly ubiquitous. In T2, we found that Canada thistle was the most common weed on level ground, but it was replaced by sweetclover as the local slope increased.

Whereas local slope exerted significant influence on species composition, the effect of relative elevation was weak or non-existent. This may be attributed to the lack of uniformity along a slope. Slopes with slight undulations alternate between concave and convex curve shapes, creating microsites along their length where soil may be alternately deposited or lost to erosion. As a result, the capacity of eroded sites to hold moisture is decreased, while the capacity of deposition sites is increased. The implication is that targeting the planting of upland species to their preferred sites can be rather challenging. For example, little bluestem may generally outcompete big bluestem on the higher elevations where slopes are steeper, but higher elevations may also include small, localized concave topography with moist soils where big bluestem outcompetes little bluestem. This makes an argument for adjusting relative proportions of species in seed mixes depending upon slope position, but for maintaining all species in the mix at all locations.

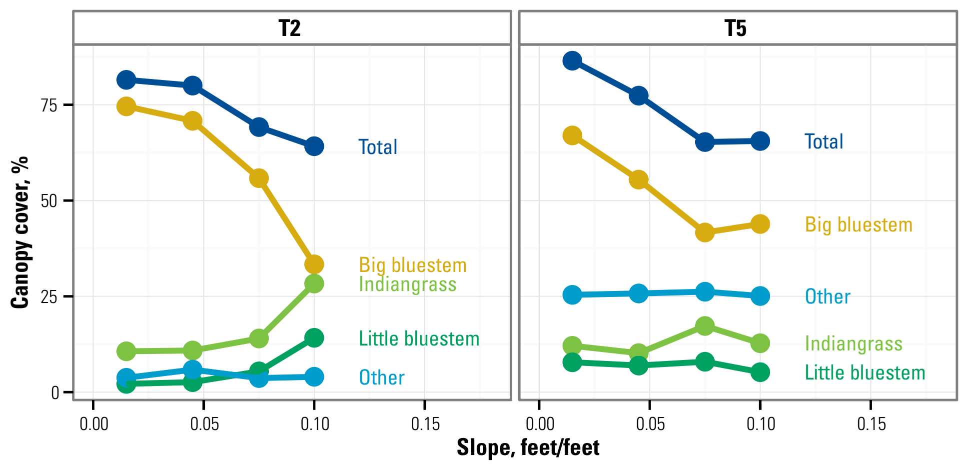


Figure 6. Canopy cover in two fields in 2014. Field T2 was planted to the 13-species mixture in 2008. Field T5 was planted to the 24-species mixture in 2010. Frequency of species occurrence is shown in Appendix Tables A2 and A3.

Selecting prairie monocultures or mixtures for upland sites		
	Pro	Con
Switchgrass monocultures	• Seed may be cheaper • More herbicide options • Ready to harvest at same time • Easily harvested for seed as well as biomass • Good yield	• Low biodiversity • Low productivity in wet or dry sites
Simple mixtures	• Can be matched to topographic position to increase yield and diversity • Moderate biodiversity	
Complex mixtures	• Increased biodiversity • Might stabilize yields over time	• Seed more expensive • Yield less over the short-medium term • More difficult to control weeds • Seed harvest more difficult

WETLAND COMMUNITIES

Some of the techniques for establishing uplands also apply to wetlands, such as the importance of a good seedbed when drilling seed. However, there are additional considerations and challenges that apply to establishing native wetland vegetation. These include the previous vegetation and seed bank, current hydrologic regime, artificial drainage, and wet soil conditions at planting time.

About 40 wetlands of various sizes occurred in the EcoSun Prairie Farm. Most of these had been previously drained and farmed, although planting was sometimes impossible and crop failures were common due to wet soils in the spring. The hydrology of the largest wetlands had been changed by construction of drainage ditches that led to a stream or natural drainage running through the property. In some areas, the stream and drainages had been channelized. To restore the hydrologic functioning and native vegetation to these wetlands, EcoSun plugged the drainage ditches and in three cases installed structures that allowed us to control the water level. Control of the water level allowed us to dry the land in preparation for planting, prevent flooding of seedlings during establishment, and then reflood during subsequent rains.

This stand pipe could be easily adjusted to control the wetland water level. Photo courtesy of Craig Novotny.

Placing species in the correct part of the landscape is especially important in wetlands because of the more rapid change in hydrology over short distances. With patience, nature itself can take care of this. We chose to accelerate the natural process in many wetlands by controling undesirable species and by scattering seed or transplanting a small number of desirable species. In other wetlands, especially the larger ones, we took a more hands-on approach by planting specific species intended for biomass and seed production. We used a variety of techniques, described below.

Prairie cordgrass (Spartina pectinata)

Prairie cordgrass forms rhizomes and spreads quickly in areas where it is well adapted. It is taller than switchgrass or big bluestem. When viewing a wetland with prairie cordgrass from a distance, this species may seem to dominate the wetland so completely that it appears to be growing in monoculture. Closer inspection, however, reveals a number of other, short-statured species such as wetland sedges growing in the lower canopy. We planted prairie cordgrass plugs and/or seed into three large wetlands ranging in size from 1 to 3.5 acres, in several smaller wetlands, and along the banks of drainage ditches.

A prairie cordgrass wetland within a field dominated by big bluestem. Photo courtesy of Craig Novotny.

Left: A new planting of switchgrass located between two fields of corn in a replicated experiment. The switchgrass seedlings are barely visible against the brown soil, which is littered with corn residue. Note the yellow color of the corn and the darker, wetter soils at the lowest elevation. Although the wet soils are lowering corn grain yield, switchgrass and prairie cordgrass perform well under those conditions.
Right: Corn is on the left of a newly-planted switchgrass field. Note a similar effect of topography and wet soils at the EcoSun Prairie Farm. Also notice the greater density of weeds in the low ground. Once established, switchgrass was able to outcompete the weeds at this site.

In 2008, we built a low berm of soil to block the artificial drainage from 2 wetlands in field T2, each ~ 1 to 1.5 acres, so that their maximum water depth would be 15 to 20 inches, the typical depth of temporary prairie wetlands in the region. Both had been farmed with soybeans in the previous year. We sprayed the wetlands with 2 quarts/acre glyphosate (Rodeo) on May 21st. Then, from May 23rd through July 10th, we planted half of each wetland with prairie cordgrass plugs at 3 feet-spacing and the other half at 5 feet-spacing. We wanted to determine whether or not the lower density would produce a dense stand as quickly as the higher density. The plugs had been grown in the greenhouse in "cone-tainers" (Stuewe & Sons, Tangent, OR). All plants were the 'Prairie Farm' variety, which originated in southeast South Dakota and was introduced to the restoration community by EcoSun (Appendix Figure A2). After one year, 91% of the plants had survived (Zilverberg et al., 2014a). From 2010 to 2014, yield from these wetlands averaged 5.3 tons/acre when harvested by hand at ground level. There was little difference in yield between the two planting densities, and the difference was only statistically significant in two years, 2009 and 2014. Therefore, due to the extra labor and cost required for a 3 feet-spacing, we determined that a 5 feet-spacing was preferable.

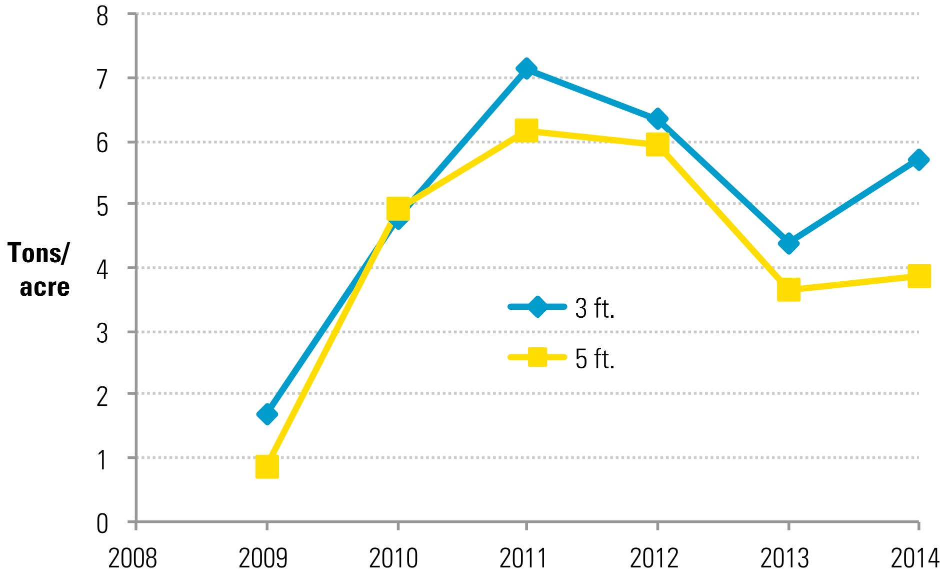


Figure 7. Biomass yield of prairie cordgrass when cut by hand at ground level. Prairie cordgrass was planted at two densities, 3 feet or 5 feet between plants. Biomass yield of the the two densities statistically differed only in 2009 and 2014.

We conducted a second establishment experiment in a 3.5-acre temporary/seasonal wetland within field T5. We kept this wetland at a maximum depth of 20 inches using the water control structure at the outlet. In 2010, we planted two varieties of prairie cordgrass, Prairie Farm and Red River, using two different techniques, direct seeding with a 10.5 feet-wide Truax grass drill or transplanting from greenhouse plugs. We also evaluated the effect of elevation on establishment success and yield. Elevation is an indication of wetness, because lower elevations have a greater above-ground water depth in the spring, remain flooded until later in spring, and are nearer the water table once they are no longer flooded. Detailed methods and results of this experiment were reported by Zilverberg et al. (2014a) and are summarized here.

We measured natural canopy height, maximum seedhead height, seedhead density, and biomass yield from the center of the wetland basin (low elevation) to the area above the wetland basin (high elevation) that was dominated by big bluestem and other upland plant species. We combined the height measurements and seedhead density into a composite vigor index.

A 3.5-acre temporary/seasonal wetland within field T5. The wetland drains to the left (west) of the photo. Near the left edge of the photo is a green line running perpendicular to the drainage. This is the control structure used to regulate water depth in the wetland. This wetland was planted to two varieties of prairie cordgrass by direct seeding or by transplanting. The experimental cordgrass transects form a green "X" centered on the deepest part of the wetland. A green ring of cordgrass is also visible around the wetland edge--this was grown for seed production and was not part of the experiment. Adapted from Zilverberg et al. (2014a).

Plugs of prairie cordgrass grown in the greenhouse were transplanted into temporary and seasonal wetlands. A dibble was used to create holes of the appropriate size.

We found that in the center of the wetland, where maximum water depth was greater than 16 inches, directly drilling seed was unsuccessful. We drilled when the wetland was dry, but after the wetland was filled, drilled seed did not germinate or seedlings died because of the water depth. In contrast, transplants were large enough to survive the deep water. In shallow parts of the wetland, both drilling and transplanting were successful. Over time, we saw an increase in "establishment" success because established plants spread, mostly vegetatively, into areas that were previously unoccupied by cordgrass. We also found that, as conditions in the wetland became drier from 2011 to 2013, the optimum location for prairie cordgrass shifted downslope towards the center of the wetland. This occurred regardless of establishment method or variety.

Seedhead density varied greatly by year, ranging from 6 seedheads/100 feet^2 in 2013 to 80 seedheads/100 feet^2 in 2011. The top leaf of the Prairie Farm variety was 4 feet high, compared to only 3 feet for Red River. Likewise, the tallest Prairie Farm seedheads averaged 6.7 feet high, but Red River was only 5 feet. This height difference might have some importance for wildlife value, since Prairie Farm cordgrass could be exposed above accumulated snow and provide winter cover longer than Red River, but this was not experimentally tested.

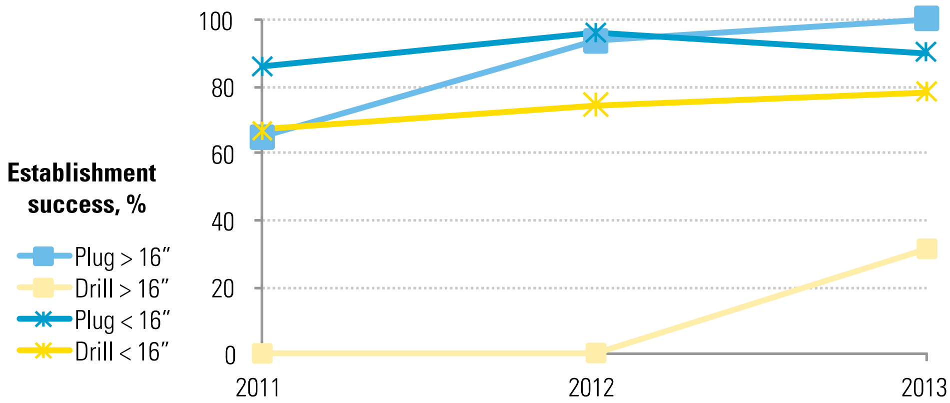


Figure 8. Success of establishing 'Prairie Farm' prairie cordgrass in the wetland in field T5 by two techniques. In the deepest part of the wetland (where maximum water depth was greater than 16 inches), directly drilling seed was unsuccessful. Where maximum water depth was less than 16 inches, both drilling and transplanting were successful. Data from Zilverberg et al. (2014a).

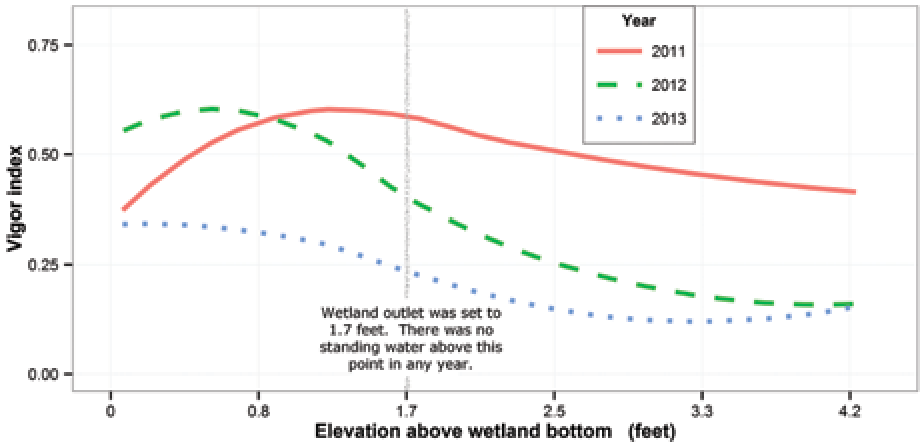


Figure 9. Vigor index of Prairie Farm prairie cordgrass, established by transplanting greenhouse plugs in the wetland of field T5. The outlet of the wetland basin was set at ~1.7 feet above the deepest part of the basin. Thus, elevation "0" was the deepest part of the wetland, and corresponds to a maximum water depth of 1.7 feet. Vigor shifted to the center of the wetland as the wetland dried out from 2011 to 2013. Adapted from Zilverberg et al. (2014a).

Despite height differences between the two varieties, we did not find statistically significant differences in biomass yield. This might be explained by our observation that Red River plants, despite being shorter, appeared to have a greater leaf density 1 to 2 feet above the soil surface compared to Prairie Farm. The biomass yield of the Prairie Farm variety was less in the T5 wetland than the T2 wetlands, perhaps due to differences in establishment success.

Besides the experiments just described, we established prairie cordgrass for seed and biomass production in other parts of the farm. This allowed us to informally experiment with alternative establishment techniques. Based on this experience, our preferred technique for establishment was to transplant greenhouse plugs with the help of a tree-planter when the soil was sufficiently dry. This reduced the labor and time required compared with transplanting by hand, it was more likely to be successful than drilling seed in deeper wetlands, and it reduced the amount of seed required compared to using a drill. Reducing the amount of seed used was important because the seed was expensive ($75/pound). In fact, using a tree planter and widely spacing transplants was cheaper than establishing with a drill despite the extra labor required for transplanting. This might change in the future as the market prices for seed and labor change.

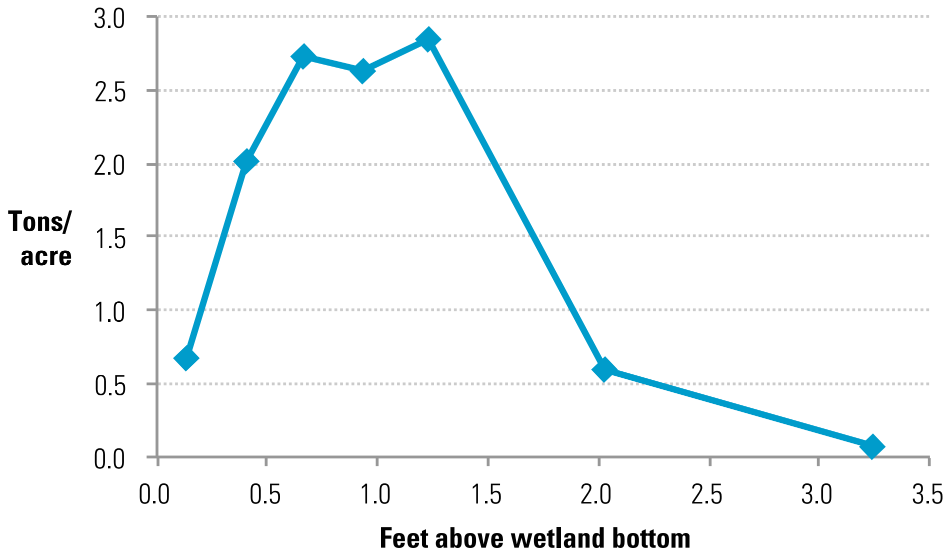


Figure 10. Biomass yield of Prairie Farm prairie cordgrass in the T5 wetland in 2013, as affected by elevation, a proxy for soil moisture, above the wetland bottom.

Recommendations for establishing native wetland vegetation

	Year 0	Year 1	Year 2
Prairie cordgrass	Raise soybeans	**Preplant:** Apply glyphosate to kill existing vegetation. **Planting date:** April to mid-June. **Planting rate:** greenhouse plants spaced at 5 feet (preferred) or 9 pounds PLS/acre. **Planting technique:** Tree planter for transplanting plugs; a grass drill can be used in dry wetlands that will not hold more than 16 inches of water when full. **Post-seeding:** Mow 1 to 2 times above the height of the grass to control tall weeds.	**Replant** areas of field that did not establish well, if necessary. **Spot-spray** with Milestone as needed to control weeds.
Prairie wedgegrass	Raise soybeans	**Preplant** and **planting date** are same as cordgrass. **Planting technique:** Grass drill (1/4-inch depth) if stubble present. Can broadcast on bare ground.	Same as cordgrass.

Prairie wedgegrass (Sphenopholis obtusata)

Prairie wedgegrass is a native wetland plant whose seed is generally not available from commercial sources. It is a short-lived perennial in the low prairie and wet meadow zones that dies after producing seed. Thus, it maintains itself in the plant community by having long-lived seeds that reside in the wetland seed bank. It germinates during drawdown periods or possibly during wet autumns and springs. It usually flowers in the second year of growth. A detailed description of its life history is available in Simon (2012), based on research conducted at the Prairie Farm. Wedgegrass has great potential for inclusion in seed mixes for wetland restoration, as the seed germinates quickly and the plant grows quickly as well. Prairie wedgegrass was planted along the lower edges of a natural drainage near field T6 and near the large central wetland. Nearly 200 pounds of seed were produced on the Prairie Farm and marketed through Millborn Seed Co. of Brookings, SD (Appendix Figure A3).

Other wetland species

American sloughgrass (*Beckmannia syzigachne*) was established in small patches on the farm but not harvested for seed. Slough sedge (*Carex atherodes*), woolly sedge (*Carex pellita*), and smooth cone sedge (*Carex laeviconica*) were transplanted into the central strip of the two temporary wetlands in field T2 where cordgrass was not planted. These sedges spread naturally within the cordgrass section of the wetland, especially where cordgrass cover was lowest. We opportunistically hand-harvested their seed.

Smooth cone sedge (*Carex laeviconica*) seeds collected near Chamberlain, SD, for EcoSun.

Chapter 4

Managing Established Plant Communities for Profit, Sustainability, and Ecosystem Services

Prairie cordgrass seedheads. Photo courtesy of Craig Novotny.

EcoSun strove for diversity in both its economic enterprises and its vegetation management of the Prairie Farm. These enterprises included production of native seed, native hay, and beef. However, Prairie Farm fields were not dedicated to a single enterprise. For example, fields harvested for seed were typically harvested for biomass in the same year, and fields grazed one year were commonly hayed the next. Thus, decisions regarding management of the farm required a holistic approach that considered production objectives of the several enterprises, economic concerns, and provision of ecosystem services.

From its inception, the farm was intended to produce biomass suitable as biofuel feedstock. However, during the farm's operation from 2008 to 2014, a commercial market for ligno-cellulosic biofuel feedstock did not develop. Therefore, much of the farm's biomass production was marketed as hay. The majority of the hay produced by the farm was harvested in autumn, after a killing frost. Harvesting late in the year results in poor forage quality but good biofuel feedstock quality because the N concentration is less. Less removal of N also means less N fertilizer is required to maintain yield levels. This is the same technique recommended for sustainable, low-input biofuel production. Therefore, the lessons learned from EcoSun's autumn harvests may also be applied to biofuel feedstock harvests.

Harvesting late in the year results in poor forage quality but good biofuel feedstock quality because nutrient concentrations are less.

SWITCHGRASS

Switchgrass covered the largest area and was the most productive (pounds/acre) of the species harvested for seed on the Prairie Farm. Three varieties (Nebraska 28, Sunburst, and Summer) were planted on the farm to diversify production and income. All three varieties were managed similarly. After establishment, switchgrass fields were annually burned in early spring. Additional spot spraying or whole-field spraying (rarely done) was required in some post-establishment years, but in other years, spring burning was sufficient to keep weeds in check. Because switchgrass fields were composed of a single functional group (warm season grass), we had a variety of herbicide options. The most common invasive plants encountered were common milkweed (*Asclepias syriaca*), green foxtail (*Setaria viridis*), and yellow foxtail (*Setaria pumila*).

The less invasive milkweed species, swamp milkweed (*Asclepias incarnata*), that grew in wetter areas of the Prairie Farm was not sprayed. Swamp milkweed is also used by monarch butterflies throughout their life-cycle. All switchgrass fields were fertilized in 2013 with 36 to 49 pounds N/acre and in 2014 with 9 pounds N and 10 pounds P/acre.

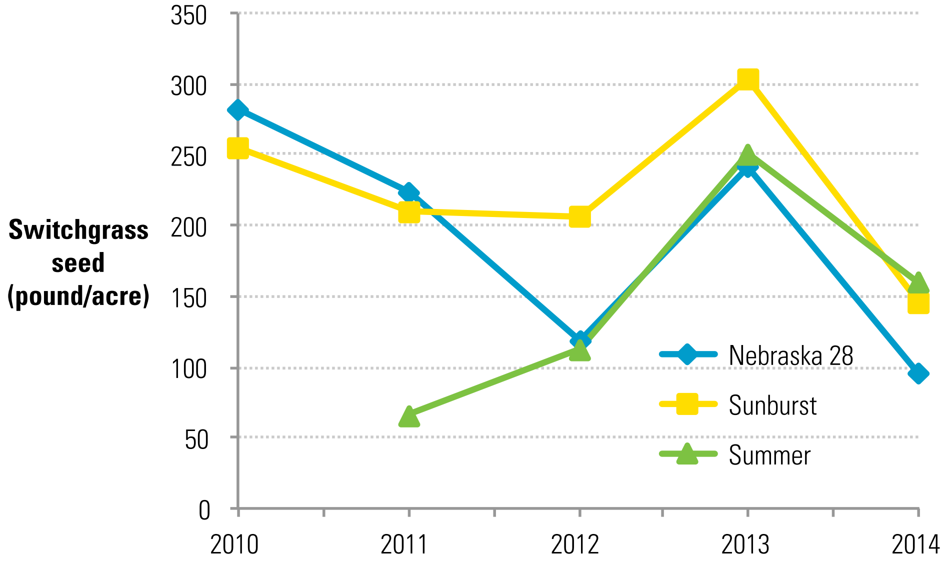


Figure 11. Seed yield of three switchgrass varieties. Nebraska 28 and Sunburst were established in 2008. Summer was established in 2010. Fields were fertilized in 2013 with 36 to 49 pounds N/acre and in 2014 with 9 pounds N and 10 pounds P/acre.

We harvested switchgrass and prairie cordgrass seed with a John Deere 3300 combine when the seed moisture content dropped to 18 to 20%, which typically occurred after a hard frost in late September or October. Seed was then transferred from the combine to a grain cart equipped with a fan and manually agitated for several days to dry the seed down to about 15% moisture content. After the seed was dry, we delivered it to a commercial seed company (Millborn Seeds), who completed the process of cleaning, bagging, and marketing.

Because each variety of switchgrass was planted in a different field, differences in seed yield among fields could be due to soils rather than to variety. Once a field was fully established (in its third year since planting), seed yield ranged from ~100 to 300 pounds PLS/acre.

At harvest, seed was loaded into grain carts and then cleaned.

After switchgrass seed was harvested, stems with leaves ~3 feet-high remained in the field, as well as non-seed residue that had passed through the combine. The stubble was cut and placed in windrows with a swather and then baled with a large round baler. In some years, windrows were dry enough to be baled immediately after cutting. In some years, two windrows were combined with a rake before baling, or turned with a rake if they had been rained on. Yield ranged from 2.1 to 2.8 tons/acre and price ranged from $50 to $100/ton, depending on year.

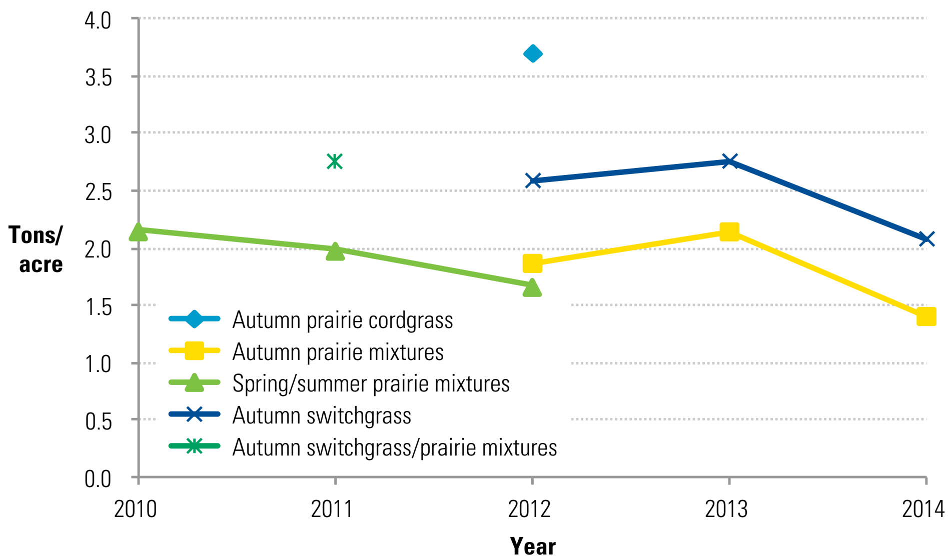


Figure 12. Hay yield of switchgrass monocultures, mixtures of upland prairie species, and a prairie cordgrass-dominated wetland when harvested by a commercial windrower and baler. Not all fields were harvested in all years. Switchgrass and prairie cordgrass were harvested for seed prior to the stubble being harvested for hay. Data from 2010 to 2012 were previously published in Zilverberg et al. (2014b).

BLUESTEM-DOMINATED MIXTURES

Bluestem-dominated mixtures included some fields that were in a corn-soybean rotation and others that were in CRP when EcoSun assumed management. All restored fields (whose names begin with "T" for "Tilled"; T2, T4, T5, T6) were dominated by warm season grasses, especially big bluestem. Some of the former CRP fields (whose names begin with "C") were similarly dominated by warm season grasses after being renovated by EcoSun (C1, C2), but in others (C4, C5, C6), exotic cool season species dominated, even after renovation.

As seed mixtures increase in diversity, weed control becomes more challenging because the timing of herbicide application and available herbicides become more limited. For instance, a general broadleaf herbicide such as 2,4-D will damage native forbs if used when they are actively growing. To avoid damaging the native forbs planted in fields T4 and T5, we primarily relied on Milestone herbicide. Even so, Milestone did cause some damage to the native forbs. Therefore, we always attempted to minimize the amount of herbicide used by first applying herbicide by spot-spraying, and only resorted to whole-field herbicide applications when absolutely necessary. For intermediate cases, we used a boom sprayer mounted on a 4-wheeler. The most troublesome weed was Canada thistle. If it became apparent that we had not adequately controlled Canada thistle with herbicide in field T2 or T5, we spot-mowed some areas of the field at a height to prevent the thistle from producing seed but to remove a minimum of desirable vegetation. In fields that did not contain native cool season grasses, we occasionally used spring burns or spring application of glyphosate to control cool season grasses. The bluestem-dominated fields were not fertilized except for an experimental strip in 2014.

Fields were usually harvested for hay in autumn, after plants had a chance to translocate N & P to the crowns, resulting in less export of valuable nutrients away from the farm.

Managing for hay and grazing

All of the mixed-species plantings were grazed in at least one year. All but the most rugged (C4, C5, and C6) were also hayed in at least one year. In a few instances, the same field was hayed in late spring/early summer and then grazed in late summer/early autumn, or vice versa. Grazing regrowth of warm season grasses in late summer provided higher quality forage than would have been available otherwise.

The largest, highest-quality fields were intentionally managed with a diversity of harvest techniques to encourage plant species diversity and reduce weed pressure. For instance, fields T2 and T4 were not grazed for more than two consecutive years. In years when they were not grazed, they were harvested for hay after going dormant. Part of T5 was grazed every year, but which areas were grazed and which were hayed varied by year. Allowing the vegetation to reach maximum growth and close the canopy before an autumn harvest reduced the amount of light reaching shorter, weedy species. It also allowed established species to accumulate more energy reserves for future growth.

Spring- and summer-harvested hay is more valuable ($/ton) than autumn-harvested hay because of its higher digestibility and crude protein concentrations, but its greater nutrient (N, P, K) density results in exporting more nutrients. Thus, over the years, EcoSun shifted from harvesting spring/summer hay to harvesting hay in autumn to conserve nutrients on the farm and control weeds.

Each spring, we determined which fields would be grazed and which would be harvested for hay. Besides providing diversity in management and income streams, planning for both grazing and hay allowed us flexibility with stocking rates. That is to say, although the number of grazing heifers was fixed for most of the grazing season, we could graze more (or fewer) acres in a bad (or good) year and hay the balance.

Beginning in 2011, we annually contract-grazed approximately 75 yearling heifers from the Mortenson Ranch, winner of the 2011 Leopold Conservation Award in South Dakota. The exotic grasses in one of the farm's pastures (described in the following section) broke dormancy and "greened-up" earlier than the native cool and warm season grasses found in field T5. Therefore, when we took delivery of the heifers (mean weight: 797 pounds) in May, they began their time on the farm grazing the exotic grasses. We divided this pasture into 3 to 4 paddocks and grazed each ~1 week before moving to the next paddock. In early June, after ~1 month of grazing exotic grasses, the heifers were moved to restored fields dominated by native grasses.

For the next several months, the heifers mostly grazed bluestem-dominated pastures, which were subdivided by temporary electric fencing. We moved the heifers to a new paddock about once per week, but actual frequency varied with the rate of grass growth and paddock size. Some of the smaller fields (i.e., C4, C5, and C6) were grazed together with larger pastures. In midsummer, the heifers were typically given simultaneous access to the exotic and restored pastures for up to one month. We did this because the exotic vegetation had regrown and the wetlands and waterways found in the exotic grass pasture helped cool the cattle when air temperatures were high.

In September or October, the heifers returned to the exotic pasture for 1 to 2 months of grazing. In mid-October, most of the heifers were sold at a nearby livestock auction. The remainder (5 to 30) was retained until November, when they were slaughtered and butchered (mean weight: 949 pounds). The heifers received salt and mineral supplements throughout the grazing period. Average daily gain for the entire grazing period and all years was 0.67 pounds. The meat (19,000 pounds) was marketed and sold as "Prairie-raised" lean beef in local restaurants (Parker's Bistro, Cottonwood Bistro), grocery stores (Co-op Natural Foods, Pomegranate Market), on the SDSU campus (Agricultural Heritage Museum), and directly to consumers. It was also marketed in the eastern U.S. by the startup company, NuAgra.

"Prairie-raised" beef was marketed locally under the EcoSun brand.

Bluestem seed harvest

Planting a monoculture facilitates the harvest of seed because it is easy to harvest a single species. However, because big bluestem's seed heads rise above those of any other species in the mixture, it is also possible to harvest pure big bluestem seed from a mixed-species planting. We did this in only one year, 2014, when the price of big bluestem seed was higher than normal, compared to switchgrass. Our yield of 'Sunnyview' big bluestem was 85 pounds PLS/acre from field T4 and we sold it at $2.50/pound PLS. Thus, bluestem-dominated pastures generated income from five sources: 1) summer hay, 2) autumn hay, 3) contract grazing, 4) prairie-raised beef, and 5) big bluestem seed. A record of which harvests were conducted each year are reported by field in Appendix Table A4.

EXOTIC COOL SEASON PASTURE

The farm included 75 acres of exotic, cool season pasture dominated by smooth brome (*Bromus inermis*), crested wheatgrass (*Agropyron cristatum*) and Kentucky bluegrass (*Poa pratensis*). The pasture had been grazed annually by beef cattle before EcoSun assumed management. We planted cottonwood (*Populus deltoides*) trees near a dugout and controlled noxious weeds, but no large scale attempts were made to restore this pasture to native plant mixtures. Instead, we integrated the pasture into our grazing system, as described in the previous section.


Photo courtesy of Craig Novotny

LOCAL REMNANT PRAIRIE SEED MIX

One field (T7) on the farm was planted in December 2010 to a mixture of seed harvested from a nearby virgin prairie owned by The Nature Conservancy. We intended to manage this field similarly to the other bluestem-dominated mixtures, with the exception of individualized harvest of seed from many species in the mixture. By 2014, this field had only been in production for two years after its establishment; therefore, its full potential had not yet been realized. The diversity of species in this field made weed control especially challenging and prevented seed harvest in 2013. Weeds were less problematic in 2014, allowing us to harvest ~ 30 of the 38 total acres for seed, yielding 967 lb PLS. The entire field was harvested for hay after the seed harvest, yielding 1.1 ton/acre.

PRAIRIE CORDGRASS

Prairie cordgrass was only planted into areas of the farm that were typically flooded in spring but dry in summer—the same areas where cordgrass would be found in nature. Thus, prairie cordgrass was established in relatively small patches within a larger field or along a drainage at the edge of a field. Consequently, the many small patches were not managed homogeneously, as the switchgrass monoculture fields were. Patches were sometimes grazed or hayed with adjacent or surrounding fields, but the primary product harvested from cordgrass was always seed. We typically limited grazing of cordgrass for this reason. Cordgrass is good forage when immature, but it becomes unpalatable when mature. The coarseness of mature cordgrass inspired its other common name, “ripgut.” Mature cordgrass hay can be ground and fed as part of mixed ration.

We harvested cordgrass seed with the same John Deere 3300 combine used for switchgrass. Seed yield varied greatly from year-to-year within a given patch of cordgrass. This was likely due to changes in the population of the four-lined borer (*Resapamea stipata*), precipitation differences, and changing water table levels (Fig. 1, 9). Although we did not conduct formal studies, we observed that cordgrass seed yields tended to be higher in stands that had been burned after the previous growing season. The effect of burning on the four-lined borer was

We planted the "kidney" wetlands in field T2 to prairie cordgrass, except for a central strip in each wetland that was planted to a variety of sedges. When the field was grazed, we protected the wetlands with temporary electric fencing. Photo courtesy of Craig Novotny.

Photo courtesy of Craig Novotny.

Following an autumn burn to control the four-lined borer, prairie cordgrass grows vigorously during the following spring.

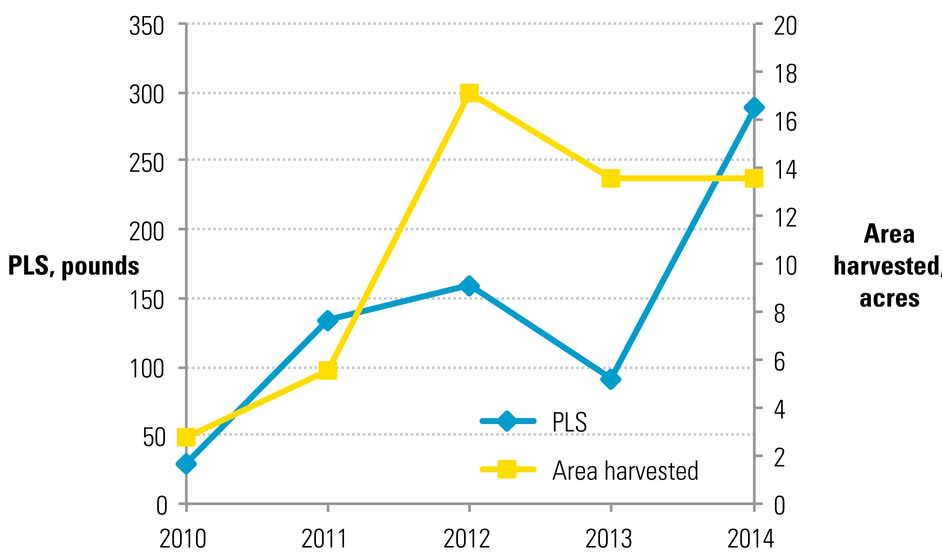


Figure 13. Quantity of prairie cordgrass pure live seed (PLS) harvested on the Prairie Farm. The area harvested increased from 2010 to 2012 as more stands matured. However, not all areas planted to cordgrass were harvested in all years. Patches of cordgrass with a low density of seedheads in a given year were not harvested because it would not have been economical.

the most likely explanation. This insect feeds on cordgrass and lays eggs on the plant's stem bases in August, so the insect is vulnerable to burning prior to hatching in April or May of the following year. For this reason, we sometimes deferred haying cordgrass in order to leave sufficient fuel for fire.

Although we planted prairie cordgrass as a monoculture, we did not manage it to maintain a monoculture. Cordgrass rapidly expands into open space using rhizomes, but before it does so, other species have the opportunity to establish themselves. Even after cordgrass was established, we observed an understory of other species, including wetland sedges. River bulrush (*Scirpus fluviatilis*) established itself in the deeper parts of wetlands that were less suitable for prairie cordgrass. Seed of these species may have already been present in the seedbank, or it may have been brought to the wetlands by waterfowl or other means. In any case, we made no effort to remove these native species. Hybrid cattail was also found in the deeper parts of wetlands during the early, wetter years of the farm. We made some attempt to remove cattails by hand-pulling, but would not recommend this technique for a typical farm. After the drier years from 2012 to 2014, the cattail population was greatly reduced naturally due to the lower water table. Because of the competitiveness of cordgrass and the frequent presence of standing water, Canada thistle was only a minor problem. Reed canarygrass invaded very slowly. Canada thistle and reed canarygrass were controlled by spot spraying.

OTHER AREAS OF THE FARM

Prairie wedgegrass was planted to a small area (~4 acres) in 2010 and allowed to reseed itself thereafter. Because it is a short-lived perennial, it is difficult to maintain long-lived monoculture stands. Therefore, it should be replanted every 2 to 3 years if seed is to be harvested. Broadleaf weeds such as pigweed and goosefoot (*Chenopodium* spp.) can be controlled with 2,4-D. Weedy grasses such as reed canarygrass and foxtail barley (*Hordeum jubatum*) can be spot sprayed with glyphosate or hand-pulled over small areas. Wedgegrass seed was harvested with a Wintersteiger small plot combine.

Many native plant species spontaneously established themselves on the farm after cessation of tillage, especially in the wetlands. We observed these species and, when a particular species produced an abundant seed crop, we manually harvested the seed with a weed eater or by hand. For instance, in 2013 we harvested $721 of pale bulrush (*Scirpus pallidus*) seed. Swamp milkweed (*Asclepias incarnata*) and needleleaf sedge (*Carex eleocharis*) were also harvested in some years.

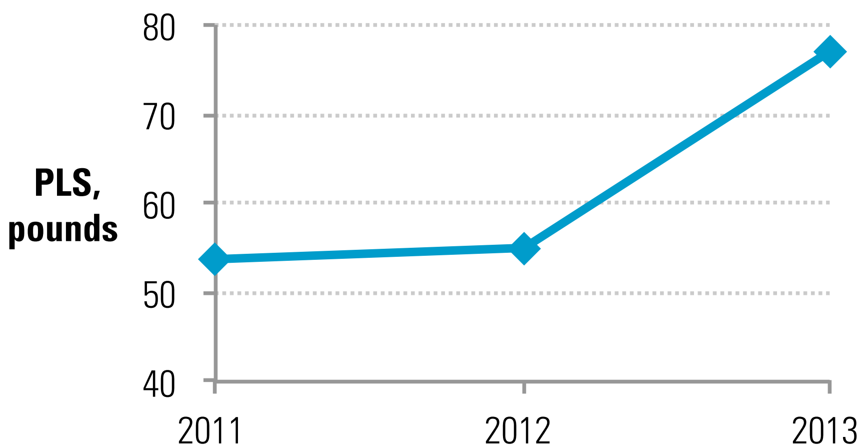


Figure 14. Yield of prairie wedgegrass seed on the Prairie Farm. Wedgegrass was planted in 2010. It was not harvested in 2014 due to a weakened stand and the invasion of foxtail barley and quackgrass (*Elymus repens*).


Harvesting prairie wedgegrass next to a field of switchgrass.

OTHER POTENTIAL ENTERPRISES

Although EcoSun derived income from a variety of sources on the Prairie Farm, others were not exploited. The most obvious of these is hunting whitetail deer, pheasants, and waterfowl, which is valued at approximately $150/person/day. Assuming 200 of the farm's 650 acres could support 100 man days, this would be the equivalent of $75/acre/year, for a total of $15,000. Some hunting occurred on the farm, but no fees were charged. Fee hunting would have required few if any changes in management on the farm and could therefore be considered very compatible with its current operation. Another potential source of revenue from current farm activities is the sale of carbon credits. The restoration of native vegetation on cropland can sequester large quantities of carbon over an extended period of time; however, the market for credits is currently weak.

An enterprise similar to the activities already in place on the farm would be intentional cultivation of other seed crops, such as native wildflowers and legumes. Although demand for these species might be less than for switchgrass, adding several native forbs to the seed harvest could have diversified and augmented income streams.

Finally, this farm would be potentially attractive for a number of agritourism activities. The agritourism industry is growing as the U.S. population becomes more interested in the sources of their food. Farms throughout the U.S. invite tourists to explore their farm in a number of ways, including extended farm tours, bed and breakfasts, weddings, and even foot races. These activities are especially appealing to EcoSun because they would educate the public while generating revenue. However, all of them would also require significant investments in capital and/or labor.

Recommendations for post-establishment management of prairie species.	
Switchgrass monocultures	Apply a **spring burn** for weed control, especially invasive cool season grasses. **Spot spray** with Milestone to control Canada thistle and other thistles. A **boom sprayer** may be used to spray the entire field in years of bad weed infestation.
Mixtures of prairie species	**Spot spray** with Milestone and **spot mow** to control Canada thistle and other thistles. A **boom sprayer** may be used to spray parts of the field if bad weed infestation occurs. **Spring burns** should not be conducted every year if native cool season grasses are present. **Glyphosate** may be applied in early spring to control invasive cool season grasses if native cool season grasses are not present. Glyphosate may also be used in late autumn, when thistle is still green but other plants are dormant.
Prairie cordgrass	Apply a **spring burn** if you intend to harvest seed. **Spot spray** with an approved aquatic herbicide, such as Rodeo, to control weeds.

Chapter 5

Ecosystem Services: Soil

Grass stubble holds the soil in place above a drainage ditch. Photo courtesy of Craig Novotny.

Tilled soils quickly lose organic matter critical to maintaining tilth, and soils not protected by crop residue or roots of perennial plants can quickly erode under high winds or heavy rain showers. Although deterioration happens quickly, rehabilitation of soils is a much slower process and is difficult to detect over the time frame (7 years) that EcoSun operated the Prairie Farm. Therefore, we focused soil sampling efforts in three major areas: 1) comparison of the farm's soils to a nearby virgin prairie with soils of similar type, 2) soil quality measures that are sensitive to short-term changes, and 3) status of the macronutrients nitrogen (N), phosphorus (P), and potassium (K).

LONG-TERM CHANGES IN SOIL DUE TO HISTORIC CROP FARMING

When archived soil samples are not available for a site of interest, it is common to compare it to a nearby site with similar soil types, in order to infer how differences in long-term management have impacted soils. This approach was taken by Olson et al. (2014) to compare soils on the Prairie Farm, which had been farmed for a century, to soils in The Nature Conservancy's "Sioux Prairie," which had not been farmed. They found that, compared to the prairie, the farmed soils had 18% less organic carbon and 16% less total nitrogen in the upper 20 inches. These differences were less than expected based on similar research done in this and other geographic areas. The small differences may be due to the fact that the portion of the Sioux Prairie that was sampled for this experiment had been heavily grazed from 1945 to 1971 and invaded by smooth brome. In addition, this study did not account for a change in soil mass due to compression of the topsoil brought about by farming practices. This could have contributed to lower estimates of C & N loss. Increases in bulk density near the surface result in more subsoil being included in a sample, resulting in a greater mass of soil when the sampling depth remains constant. The use of an equivalent soil mass method reduces this problem. At an adjacent site that was less heavily grazed and with lower density of smooth brome, our preliminary results from an analysis of similar data suggest losses of C & N due to farming are greater than 18% (Zilverberg et al., manuscript in preparation).

Heimerl's thesis (2011), which also compared the Prairie Farm with the Sioux Prairie, found that surface soils (0 to 2 inches) of uplands had lost at least 50% of their soil organic matter, particulate organic matter, microbial activity, and water aggregate stability due to farming. The same was true of wetlands, except for water aggregate stability, which was 20% lower on farmland than on prairie. Bulk density and pH of the farmed upland soils were also higher than prairie, but there was no difference in bulk density or pH in the wetlands.

The results of these studies indicate the degree of degradation that has occurred due to a century of farming. As such, the values probably represent the upper bound of the type of improvement that could be made to these soils if they were returned to native prairie cover for 100 or more years.

AVAILABLE SOIL NUTRIENTS AND NUTRIENT BALANCES UNDER ECOSUN'S MANAGEMENT

Soil test results are commonly used to help establish fertilizer recommendations for the next year's cropping season. EcoSun also conducted the tests to monitor changes in nutrient concentrations, or lack thereof, under continuous perennial biomass cover. We collected multiple soil samples (0 to 6 inches depth) annually from each major field and land use, including land remaining in annual cropping. In 2013 and 2014, we also collected soils from the Nature Conservancy's Sioux Prairie. Soil tests (nitrate, extractable P, and plant available K) were conducted by SDSU and commercial soil testing facilities from 2010 to 2014.

Extractable P and available K (the sum of soluble and exchangeable K) represent the pools of

P and K that are potentially available to plants during the growing season. Nitrate nitrogen represents a transient pool of N in the soil. Nitrate levels are typically low in soils where perennials are growing because the nitrogen is quickly incorporated into soil organic matter. Ready supplies of nitrate-N are required for concentrated grain development which takes place in relatively short periods of time in annual crops. For annual grain crops, nitrogen typically needs to be added as fertilizer (inorganic or organic) to supplement N obtained from other sources, including legumes, deposition of N in rainfall, and N released from organic matter during ammonification. During the growing season, the nitrate-N pool is replenished through mineralization of organic matter. Non-grain perennial crops often require less N than grain crops; as an example, a 200 bushels/acre corn crop removes 160 pounds/acre/year of N, whereas a 3 tons/acre crop of mature bluestem hay only removes 35 pounds/acre/year of N.

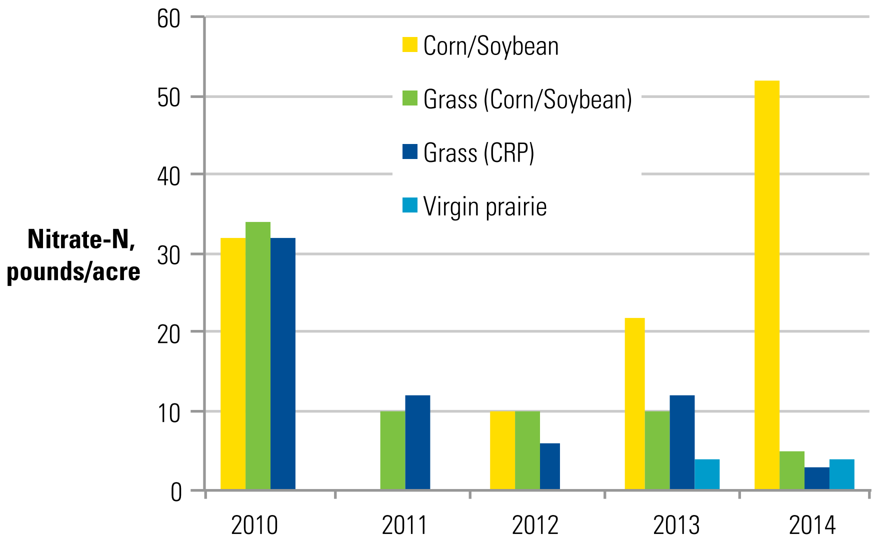


Figure 15. Nitrate-N concentration of Prairie Farm fields in corn-soybean rotation, of fields planted to grass that were previously farmed as a corn-soybean rotation or were in CRP, and of a nearby virgin prairie. There was more variation from year-to-year than from annual crops to perennial grasses. Data were not collected on the corn-soybean rotation in 2011 or the virgin prairie from 2010 to 2012.

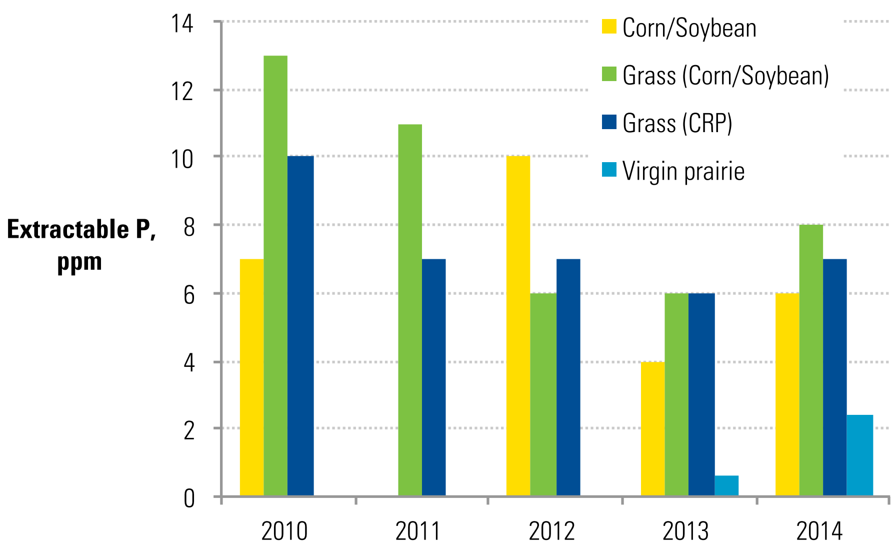


Figure 16. Phosphorus concentration of Prairie Farm fields in corn-soybean rotation, of fields planted to grass that were previously farmed as a corn-soybean rotation or were in CRP, and of a nearby virgin prairie. Data were not collected on the corn-soybean rotation in 2011 or the virgin prairie from 2010 to 2012.

For a given year, nitrate concentrations were similar across cropping systems. High nitrate for all systems in 2010 was likely due to a difference in N mineralization at sampling time, which was later than in other years. It could also be caused by carry-over of nitrate-N from the previous growing season. Based on these results, we determined that N fertilization should be continued for switchgrass seed production fields and considered for others on a field-by-field basis, considering each field's export of nutrients in hay, seed, and meat.

Soil extractable P levels were similar for all cropping systems, but like many prairie soils, extractable P levels were low. Based on these results, we determined the addition of small amounts of P combined with N may be appropriate for seed production areas of the farm.

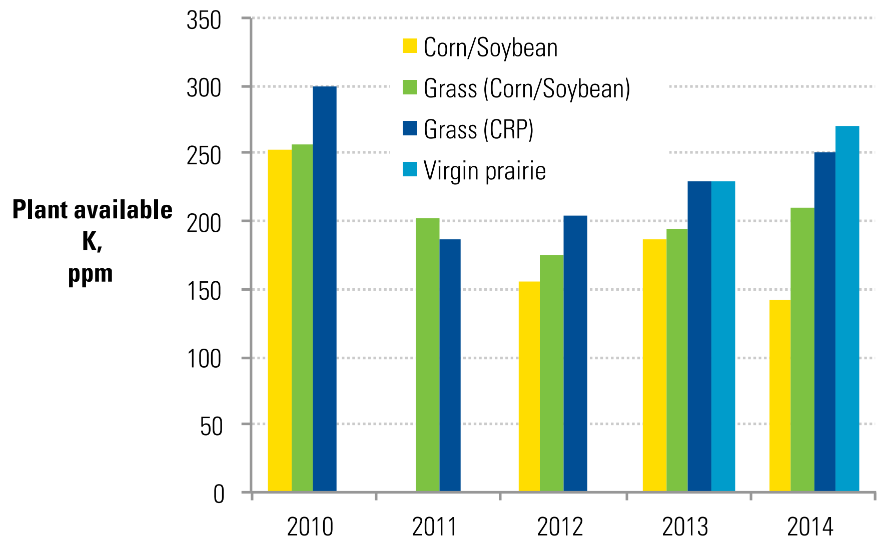


Figure 17. Potassium concentration of Prairie Farm fields in corn-soybean rotation, of fields planted to grass that were previously farmed as a corn-soybean rotation or were in CRP, and of a nearby virgin prairie. Data were not collected on the corn-soybean rotation in 2011 or the virgin prairie from 2010 to 2012.

Plant available K values were similar for all cropping systems. Annual variation in the amount of plant available K was likely due to differences in temperature and moisture from one year to the next. Because K levels were very high, we determined no K fertilizer should be added at this time, but K levels should continue to be monitored if nutrients continue to be exported as hay.

In addition to conducting soil tests, we made estimates of the quantity of macronutrients (N, P, K) removed and added to the farm. Macronutrients were removed from the site in hay, weight gained by grazing heifers, and seed. Macronutrients were added to the site via atmospheric deposition of N, symbiotic fixation of N by legumes and bacteria, and commercial fertilizer application of N and P. Calculations were based on values in the following table. Limited research (e.g., Tjepkema and Burris, 1976) also suggests that biologically significant quantities of N are being fixed by microorganisms living in association with perennial grass roots, such as switchgrass, but the magnitude of this is not well known.

Nutrient concentration of products harvested, based on literature values or on-farm measurements, and measured rates of nutrients added at EcoSun Prairie Farm.			
Nutrients removed	**N**	**P**	**K**
Seed	1.90%	0.29%	0.43%
Switchgrass straw	0.64%	0.06%	1.39%
Dormant hay	0.80%	0.14%	1.39%
Summer hay	1.00%	0.14%	1.39%
Cattle weight gain	0.74 – 0.94%	0.67%	0.30%
Nutrients added			
Mineral fertilizer	0 to 49 pounds/acre/year	0 to 10 pounds/acre/year	0
Atmospheric deposition	5.4 pounds/acre/year	0	0
Biological fixation	0 to 5 pounds/acre/year	0	0

Because the exact nutrient concentrations, atmospheric nutrient deposition, and biological N-fixation were not known, our estimates should not be regarded as precise measurements. However, they indicate that annual removal of nutrients was low, and most of the N and P was replaced. The values given in Figure 18 are annual means from 2009 to 2014, but not all activities occurred in all years.

SHORT-TERM CHANGES IN SOIL UNDER ECOSUN'S MANAGEMENT

Erosion is problematic because it reduces productivity and damages water quality by placing sediment and polluting nutrients, such as N and P, into water bodies. After assuming management of the farm, we observed severe rill erosion occurring on the farm's corn and soybean fields during high-intensity rain events early in the growing season, but not on the adjacent restored grassland.

We used the WATEM (Water And Tillage Erosion Model; Van Oost et al., 2000) model to estimate annual erosion due to tillage and water movement under conventional tillage, which was representative of the farm's previous management, or under perennial grasses. The results indicated that most of the erosion occurred prior to the adoption of mulch tillage, which probably occurred in the 1970's or 1980's. Conversion to perennial grasses further reduced water and tillage erosion by up to ~40 tons/acre/year compared to mulch tillage, depending on landscape position. In addition, perennial grass cover reduced deposition of eroded soil in waterways.

The farm received a 4.8-inch rain on May 6, 2012 that caused rill erosion in field T8 and soil was washed into the adjacent ditch. Field T8 was the only field that was not under EcoSun's management and it was still farmed in a corn-soybean rotation. In the restored fields, the only erosion occurred where vehicle tracks had killed the vegetation and left the soil bare.

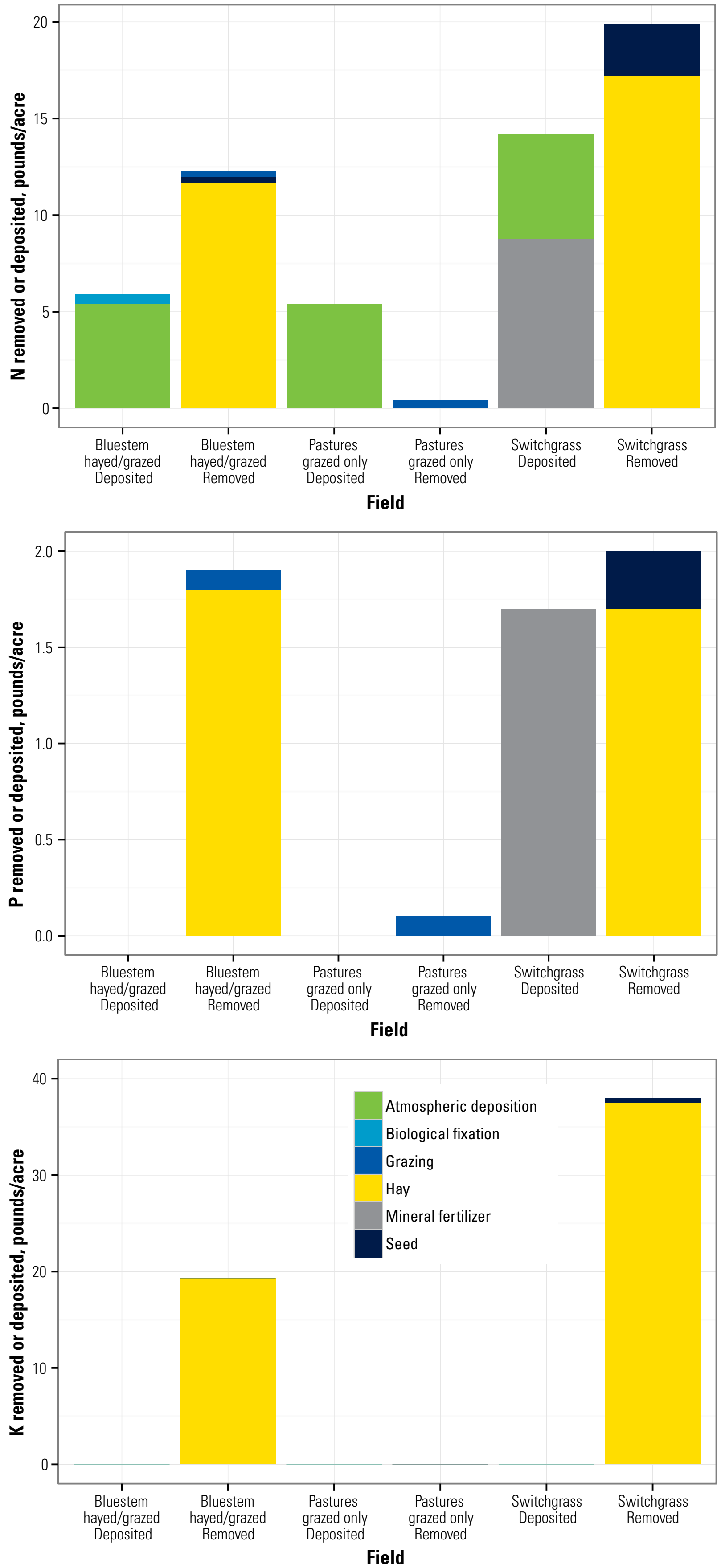


Figure 18. Average annual deposition and removal of N, P, and K from Prairie Farm fields. Not all harvest operations were conducted in all years. The y-axis differs for each nutrient.

Before long-term changes, such as soil organic carbon, are detectable, other measures can indicate management-induced soil changes. Particulate organic matter, aggregate wettability, wet aggregate stability, and measures of microbial activity are four such measurements related to agronomic and ecological performance. To measure microbial activity, a revised laboratory technique, (fluorescein diacetate assay), was developed as a part this experiment (Schumacher et al., 2015). For one experiment, we collected soils to a 6-inch depth from four management types: switchgrass that had been planted three years earlier, long-established exotic cool season grass pasture, continuous corn, and the nearby remnant Sioux Prairie, which had never been tilled. In a separate, but similar experiment, we collected soils to a 6-inch depth from 4 replicates each of corn, switchgrass, and a prairie mixture dominated by big bluestem. Samples were collected annually for 3 years following grass establishment. Before establishment, the perennial grass plots had been part of the corn field. The corn and switchgrass treatments of the experiment were repeated at a different farm near Flandreau, SD as well. Results were summarized across sites.

Two to three years after planting switchgrass and the prairie mixture, wet aggregate stability and microbial activity were both greater in grass soils than in corn. This showed that planting grass increased soil quality over a relatively short period of time. However, switchgrass still had lower wet aggregate stability than the pasture or remnant prairie, suggesting potential to continue improving.

Three years after planting grasses, switchgrass, the prairie mixture, and corn soils differed little or not at all in particulate organic matter and aggregate wettability. The lack of difference between corn and planted grass for these measures was probably due to low yields while grass was still establishing in the initial two years. With respect to these measures of soil quality, the soils with a cropping history were worse than the long-term pasture and remnant prairie. Particulate organic matter was greatest in the remnant prairie.

Conclusions and recommendations for soil management of perennial biofuel systems in eastern SD.

	Conclusions	Recommendations
C & tilth	Improvements in tilth were apparent within 3 years of planting perennials, but more time is needed to increase total soil organic matter and organic C.	Plant perennials on formerly tilled fields to improve soil tilth and sequester C.
N	Seed production and grazing removed relatively little N, compared with hay.	Fields that are hayed should have N replaced with fertilizer, assuming they do not contain many legumes. Nitrogen does not need to be added every year.
P	Hay fields lost ~2 pounds P/acre/year.	Fields that are hayed should have P replaced with fertilizer, but this need not be done annually.
K	Hay fields lost 20 to 40 pounds K/acre/year but soil tests indicated very high levels of K.	It is not recommended to apply K fertilizer on K-rich soils like those of the Prairie Farm.

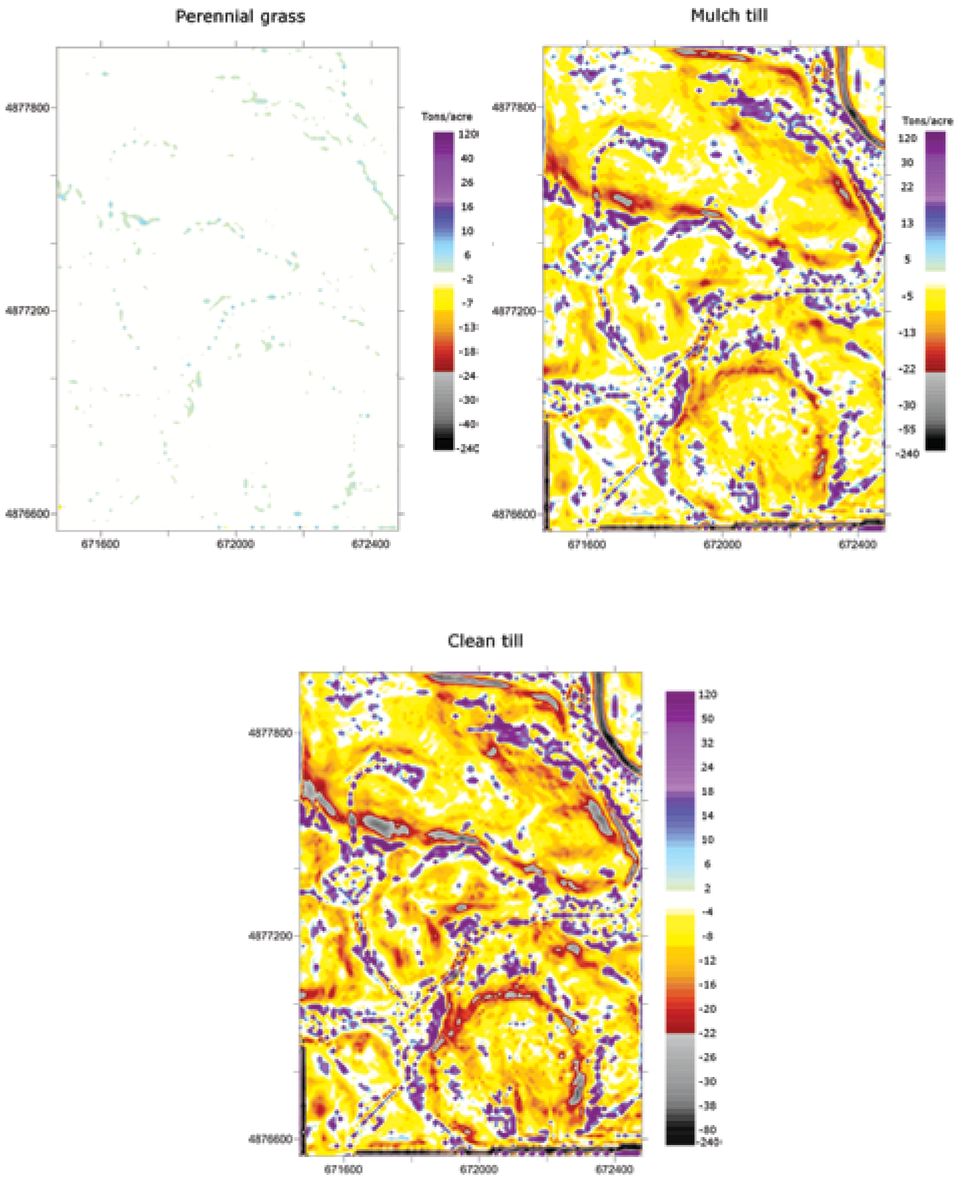


Figure 19. Estimated erosion due to tillage and water movement under three management scenarios, using the WATEM (Water And Tillage Erosion Model; Van Oost et al., 2000) model. The model considers topographic data, farm management, soil type, and climate. Negative numbers indicate topsoil loss from erosion; positive numbers indicate deposition. Scenarios included: 1) "clean till" with a moldboard plow, which was common until the mid 1970's or 1980's; 2) "mulch till" with 10 to 15% residue cover, accomplished with a chisel plow and secondary tillage, which is currently the dominant regional tillage practice; and 3) perennial grasses. Axes on the maps are from the WGS84/UTM (Universal Transverse Mercator) Zone 14N: Cartesian coordinate system, in meters. The parameters used to run the model were as follows: 1) "clean till": ktill =(Plow) 313 + (Disk) 69 + (Disk) 69 + (Harrow)78 + (Field cultivator)13= 542. WaterErosion: R=100, c=.34, k=.32, BD=1350; 2) "mulch till": ktill= (Chisel Plow) 158 + (Disk) 69 + (Disk) 69 + (Harrow) 78 + (Field Cultivator) 13= 387. WaterErosion R=100, c=.24, k=.32, BD=1350; 3) "perennial grass" ktill= 0. WaterErosion R=100, c=.01, k=.32, BD=1350.

Chapter 6

Ecosystem Services: Wildlife and Water

Photo courtesy of Craig Novotny.

DEFINITION OF ECOSYSTEM SERVICES

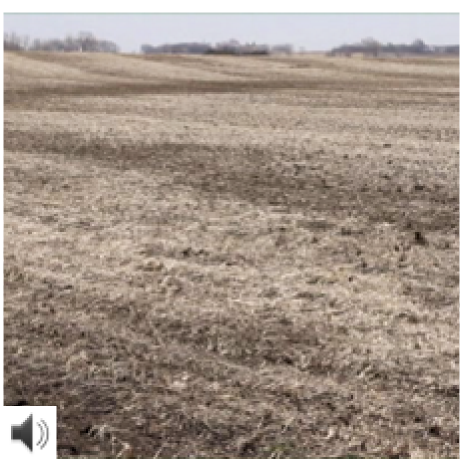
Natural ecosystems provide numerous services to humans without charge. Among these services are: water purification, wildlife and other biodiversity, climate protection, high soil quality, and goods such as timber and forage. Replacing lost ecosystem services can be costly (Gascoigne et al., 2011). Currently, considerable effort is being made to monetize these services as a means of attaching economic value to them (Leitch and Hovde, 1996) and to justify restoration and preservation of natural ecosystems. Many ecosystem services on the Prairie Farm, lost nearly a century ago when the prairie sod was broken and the wetlands were drained, returned when the landscape was restored for the experiment. These are discussed below.

WILDLIFE

It was expected that conversion of 400 acres of cropland, revitalization of CRP, restoration of several dozen wetlands, and 2 years of rest on a grazed pasture, would produce a dramatic change in wildlife numbers. This expectation was realized during the restoration process with increases in bird and amphibian species and numbers. Grassland birds that are in severe decline throughout the Great Plains because of the loss of grassland habitat (McCracken, 2005) became abundant on the Prairie Farm. During field days and associated bird walks, large numbers of obligate grassland birds were observed. These included the Grasshopper Sparrow, Savannah Sparrow, Dickcissel, Bobolink, and Meadowlark. Upland Sandpipers nested during one summer and a rare tall grass prairie obligate, the Le Conte Sparrow, was observed in June on a breeding territory. Flocks of Bobolinks, a species becoming rare in the Midwest and Great Plains, numbering from 50 to 100 birds (mixed flocks of young and adults), were observed foraging on the Prairie Farm after the breeding season but before fall migration.

Mallard and Blue-winged Teal ducks commonly nested in the restored grassland near restored wetlands throughout the Prairie Farm. Flocks of dozens of Blue-winged Teal staged on the Prairie Farm during the late summer in advance of fall migration. Other obligate wetland birds were also observed nesting, including the Sora and Virginia Rail, Sedge Wren, American Bittern, and Black-crowned Night Heron. As many as 100 species of birds, including 3 species of geese, rested and foraged on the Prairie Farm during both spring and autumn migration.

The spring soundscape of the restored wetlands was dominated by frog and toad calls. Several wetlands were monitored throughout the late spring and early summer in 2009. Four amphibian species dominated the calls recorded at night. These were the Chorus Frog, Spring Peeper, American Toad, and Leopard Frog. These amphibians were abundant in most of the restored



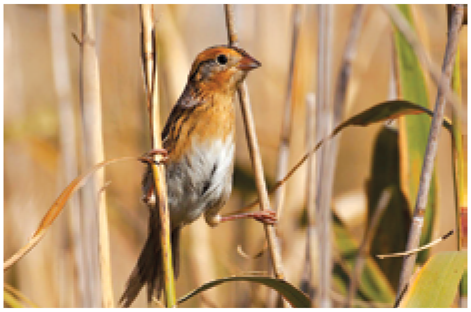
View of a farmed wetland before planting, and a similar wetland after planting. Download and open this publication in Adobe Acrobat Reader and use the icon to hear audio of the "soundscape" of each wetland. (Note: all you can hear near the farmed wetland is wind!)


Dragonfly on prairie cordgrass leaf.


Bobolink
Photo courtesy of Doug Backlund.


Dickcissel
Photo courtesy of Doug Backlund.


Grasshopper Sparrow
Photo courtesy of Doug Backlund.


LeConte's Sparrow
Photo courtesy of Doug Backlund.


Sedge Wren
Photo courtesy of Doug Backlund.


Upland Sandpiper
Photo courtesy of Doug Backlund.

temporary and seasonal wetlands on the Prairie Farm in the second growing season following restoration, pointing out how quickly these frogs and toads colonized new habitat. The soundscape during corn and soybean farming differed greatly from the soundscape during the years of the Prairie Farm project (click icons on the photos to hear clips recorded in 2009). Comparison of recorded soundscapes over time are now being promoted as a technique to identify temporal changes in the health of ecosystems (Dumyahn and Pijanowski, 2011).

WATER BUDGET AND QUAILITY

The scientific literature is replete with studies that contrast the water budget of farmed versus natural landscapes. In general, permanent vegetation cover and the presence of soil macropores (destroyed by tillage) increases infiltration and decreases runoff (Eynard et al., 2004; Lindstrom et al., 1999). Putting more water underground recharges aquifers and reduces the hydrological flashiness of streams and rivers. Flood magnitudes and duration are usually reduced as well.

Conversion of row crop fields to perennial grassland vegetation assuredly functioned as described above. A system of stream gauges was installed upstream and downstream of the Prairie Farm to measure this, but field tiling and cleaning out of drainage ditches on upstream farms compromised the data set.

Restoration of numerous wetlands also affected the landscape water budget. Wetland basins held back more water that otherwise would have flowed directly into streams and road ditches. Some of this water also recharged shallow aquifers to provide moisture for plant growth and the multitude of organisms that inhabit saturated soil environments. In short, restoring wetland basins and converting the land to perennial agriculture stored more water on the land surface and in soils and aquifers than the prior tillage system.

The scientific literature also is clear about the benefits of perennial agriculture. First, far less herbicide, pesticide, and fertilizer were applied on the Prairie Farm than would have been applied in conventional corn and soybean rotation farming. Second, soil erosion (and hence transport of biocides and fertilizer) in fields even after heavy rains was not observed. As a result, transport off site of potentially polluting chemicals, both because of less use and the soil-binding root system of perennial grasses, would have been much reduced. Third, the water quality of streams leaving a conventional tillage farm that received considerable runoff should have been much worse than in the grassland system where the water is released slowly to aquifers before entering steams.

Chapter 7

Economics, Energy Use, and Greenhouse Gas Emissions

Photo courtesy of Craig Novotny.

METHODS OF CONDUCTING THE ECONOMIC, ENERGY, AND GREENHOUSE GAS ANALYSES

We kept records of establishment activities, management activities, and inputs used for each field. We used this information to conduct an economic analysis of the project.

We allocated the farm's machinery costs, including depreciation and repairs, to individual fields and field operations based on hours used. This was the basis for estimating costs, greenhouse gas emissions, and energy use of different production activities. Machinery needs for the farm were limited, with two small tractors (105 and 47 Hp), a mower, a small combine (70 Hp), a field sprayer, an ATV, and an ATV-mounted sprayer. Swathing and baling were custom hired. Costs for fence and water improvements were amortized over 5 years and included as annual costs beginning in the year when each improvement was made. Labor and land costs were not included, so net returns represent returns to owned land and operator labor. Seed costs were also excluded because they were paid by cost-share agreements available to producers in the region. No crop insurance or other government program benefits were included.

As grasses became established, income was generated beginning in 2010 by harvesting grass seed and native wetland plant seed, haying in early summer, haying grass residue after grass seed harvest, by custom grazing beef heifers, and by marketing grass-finished beef from some of the heifers (Table 1). Land still in row crop production was not included in the analysis.

Table 1. Annual production of grass seed, hay, and beef cattle animal grazing days.

Year	Switchgrass seed (pounds)	Other seed (pounds)	Hay (tons)	Cattle (animal grazing days)
2010	14,808	28	97	0
2011	11,207	156	343	12,031†
2012	7,573	237	384	12,031
2013	13,548	261	380	13,448
2014	6,328	4,663	346	12,014

† The 2011 value is an estimate because exact beginning and ending dates were not recorded.

We estimated greenhouse gas emissions and energy use associated with production at the Prairie Farm based on the entire farm's agricultural input use and coefficients from the GREET model (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation). Inputs included seed, herbicides, fertilizer, and fuel use.

WHOLE-FARM ECONOMICS

Gross income for the farm increased each year from $0 in 2008, when conversion began, to $157,577 in 2013, and then declined to $82,832 in 2014 (Figure 20). Expenses also increased annually from $7,531 in 2008 to $89,507 in 2013, before declining to $62,444 in 2014. Initially, expenses were primarily field preparation, seeding costs, and weed control costs. As grass became established, costs shifted toward production activities, including hay and seed harvest, livestock purchases and inputs, and beef processing costs. These costs also included additional investments in equipment, fencing, and livestock watering facilities. Finally, by 2013, fertilizer application became necessary to replace some of the harvested and exported nutrients. Fewer cattle were purchased for marketing as beef in 2014, resulting in lower expenses than the previous year. Weed control costs continued to be a significant expense throughout the period.

During the first two establishment years, net returns to land and labor were losses of $7,531 and $11,974. However, EcoSun did not convert all of the cropland to grassland in the first year. Land that was not yet converted generated revenue by being rented out. At a local cash rental rate of $139 per acre (USDA-NASS, 2015), a land owner would have generated $30,302 in 2008, $24,742 in 2009, and $7,645 in 2010 on the land not yet converted to grassland. Combined with gross revenue from operating activities, this was enough to provide a positive cash flow during establishment years. Nonetheless, low income during the conversion period could be a substantial barrier to those interested in grass farming, even when grass seed costs are covered by governmental cost-share.

After the first two establishment years, net returns to land and labor began to increase. Net income was positive by 2010, at $19,028 and increased annually to $68,070 by 2013. To put this in perspective, the median household income in South Dakota was $49,415 in 2013 (U.S. Census Bureau, 2013). A combination of low prices and low yields made 2014 the least profitable year since 2010. Local crop land cash rents rapidly increased over the period of this analysis, from $139 per acre in 2008 to $228 per acre in 2013 (USDA-NASS, 2015). For comparison to the grassland income, this would have generated from $61,577 to $101,004 in annual income had the 443 acres of former CRP and converted cropland under EcoSun's management been rented out.

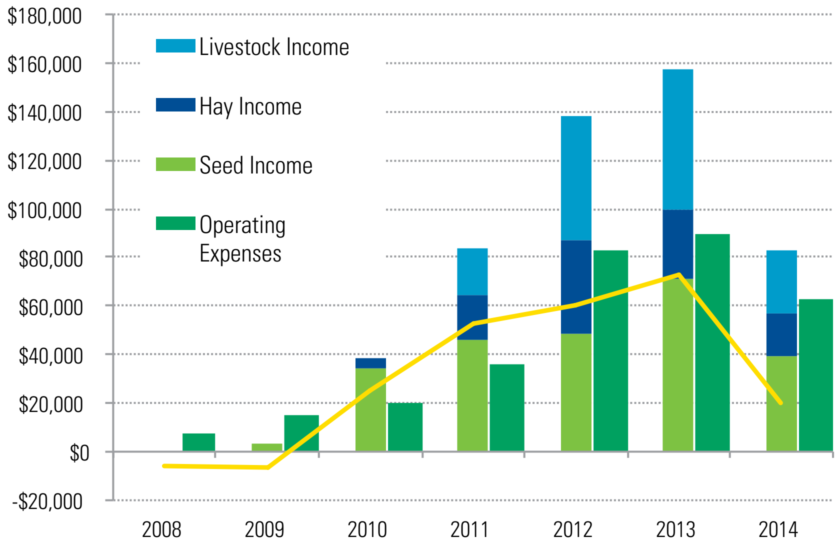


Figure 20. Prairie Farm gross income (multi-colored bars), operating expenses (solid dark green bars), and net returns to land and operator labor (yellow line).

If EcoSun had owned the Prairie Farm, rather than rented it, net income might have been improved by selling hunting rights and exploiting other opportunities for additional revenue, such as agritourism. With time, EcoSun's managers would have also gained more marketing skill, which might have resulted in additional revenue for the same level of production. However, even with this increased revenue, it is likely that renting the land for conventional farming would have produced similar revenue with much less effort. This underscores the challenge facing landowners who seek to simultaneously manage for production, profitability, and environmental sustainability with little or no government subsidies. Nevertheless, there will always be some landowners, perhaps possessing Aldo Leopold's "land ethic," who choose to operate a grass farm and forgo the lost revenue that could have been gained by converting to production of row crops.

WHOLE-FARM ENERGY USE AND GREENHOUSE GAS EMISSIONS

Both greenhouse gas emissions and energy use increased over time as more land was brought into production on the farm (Figures 21 and 22). Fertilizer was applied in 2013 to replace some of the nutrients removed in harvesting biomass as seed and hay. This led to higher greenhouse gas emissions and energy use in 2013, even though the production area did not change from the previous year.

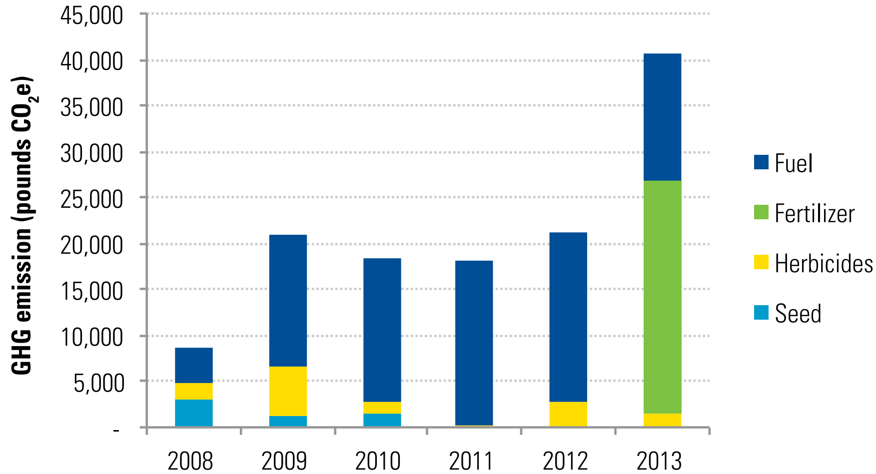


Figure 21. Whole-farm greenhouse gas emissions associated with farm inputs. Greenhouse gas emissions are reported in terms of warming potential as CO_2 equivalent emissions.

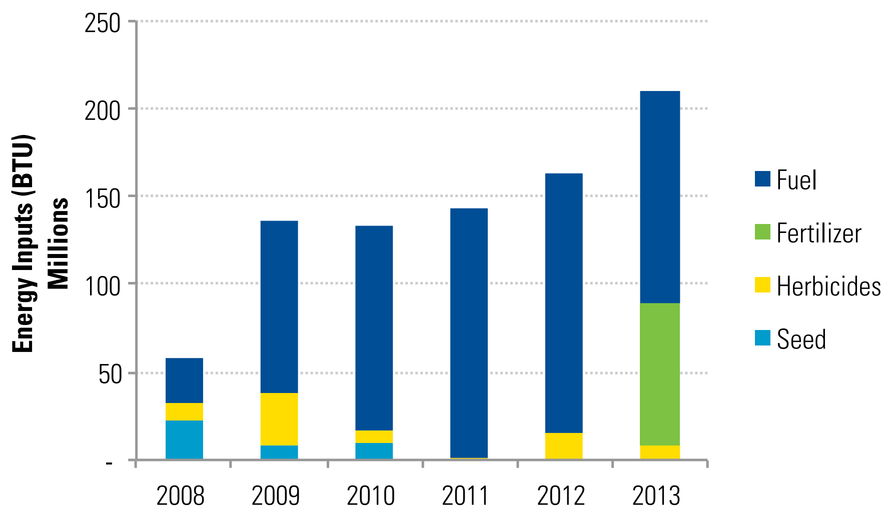


Figure 22. Whole-farm energy use associated with farm inputs.

Grasses established on the farm generated three main outputs: seed, biomass (hay), and grazing. The grazing output was an intermediate step toward generating income from livestock and beef sales. However, for the energy and greenhouse gas assessment, we need to look specifically at the biomass categories produced. Livestock grazing days were recorded for the farm, and these were converted to estimated biomass grazed, assuming 30 pounds biomass were grazed and trampled/head/day. Annual production is shown in Figure 23. Although the quantity of seed produced was relatively small compared to the biomass harvested as hay or grazed, seed production was economically important for the farm. The annual value of production is shown in Figure 24. Seed and hay values are the amounts received in actual sales. The value for livestock grazing is estimated from grazing days at a rate of $0.60 per head per day to distinguish the value of the forage grazed from the eventual value added through producing and marketing beef.

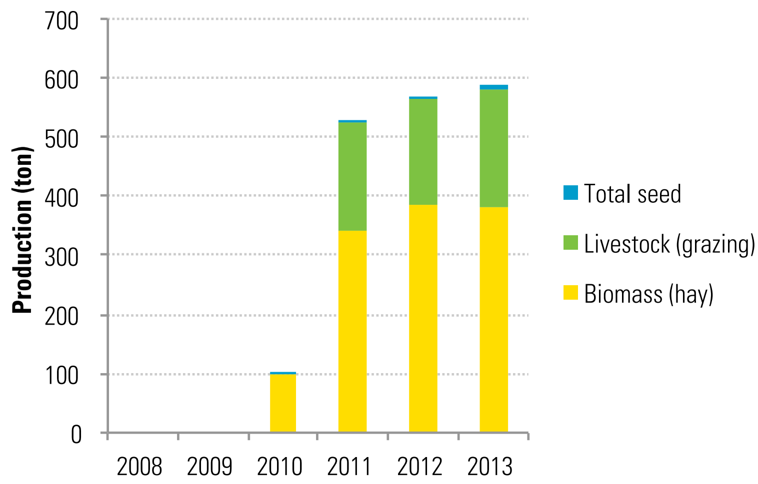


Figure 23. Annual farm output quantities as seed, hay, and estimated forage grazed by livestock.

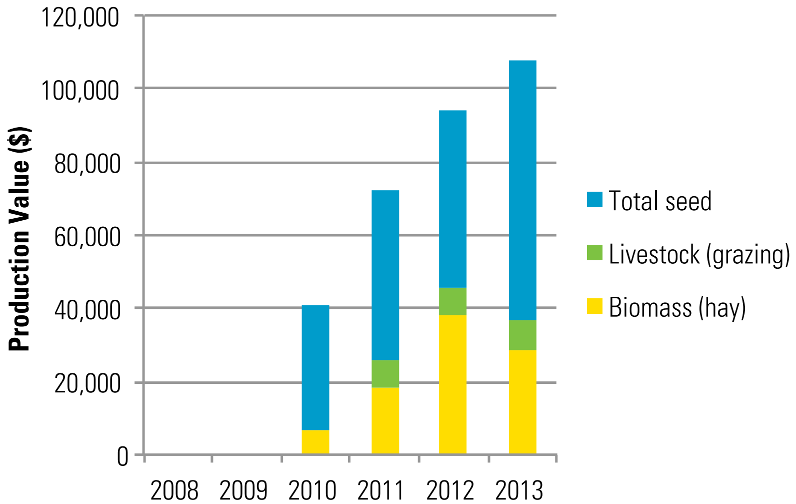


Figure 24. Value of annual farm output as seed, hay, and estimated forage value of forage grazing.

In order to look at potential greenhouse gas emissions and energy inputs associated with bioenergy feedstock production, activities specific to each output were identified and quantified separately. These included seed harvest operations which were allocated to seed production, and hay swathing, baling, and loading operations which were allocated to biomass production. Fuel use associated with these operations was estimated using agricultural engineering estimates of typical fuel use for field operations (Lazarus, 2014). All remaining operations and inputs were allocated to each output using two allocation methods: 1) based on relative production quantity (mass allocation), and 2) based on relative economic value of production (economic allocation).

Total greenhouse gas emission and energy input used for each ton of biomass produced were calculated over the period 2008 to 2013 (Table 2). Note that greenhouse gas emission and energy use are substantially higher using the mass allocation approach than the economic allocation. However, in both cases, the energy use is higher than the value (177,700 Btu/ton) used in GREET for switchgrass production. This difference between our results and GREET's value for switchgrass is primarily due to lower yields on the Prairie Farm and more herbicide use. Also, our results are averages over a five year period, while the GREET value is based on the life of a switchgrass stand, and therefore establishment energy use is spread over a longer period. As a point of comparison, the lower heating value for heat produced during combustion of switchgrass is 14,447,000 Btu/ton. Thus, the ratio of energy produced to energy used ranged from 32:1 to 62:1. However, before the Prairie Farm biomass could be used for fuel, additional energy would be needed for transportation and the conversion process, which would lower these ratios.

Table 2. Greenhouse gas emission and energy inputs per ton of biomass harvested as hay.

	Greenhouse gas emission (pounds CO2e/ton)	Energy Use (Btu/ton)
Biomass-specific production inputs	14.1	82,303
General inputs (67.2% share based on mass allocation method)	59.0	338,863
General inputs (29.2% share based on economic value allocation method)	25.7	147,380
Total (mass allocation)	73.1	421,166
Total (economic allocation)	39.7	229,683

LANDSCAPE POSITION AND SPECIES IMPACT ECONOMICS, ENERGY USE, AND GAS EMISSIONS

In addition to the farm-scale analyses, we examined in greater detail the way in which the combination of landscape position (shoulderslope, midslope, or footslope) and plant species could impact economics, energy use, and greenhouse gas emissions. Biomass yields for this analysis were based on results from a replicated small plot experiment described in a previous section. Briefly, we evaluated monocultures of species and simple mixtures of two species. Mixtures included switchgrass with a cool season grass, warm season grass, or forb species selected to be adapted to each landscape position. Each companion species was mixed with switchgrass at a rate of 0%, 33%, 67%, or 100%.

METHODS OF ANALYSIS BY LANDSCAPE POSITION

Economic enterprise budgets were constructed for each treatment and were used to estimate the farm-gate biomass prices that would be necessary for each treatment to be economically competitive with corn production. The gas emissions, energy, and economic calculations were based on the assumption of a single establishment year, followed by 11 years of biomass production. Field operations for the analysis were based on the field operations used in establishing grasses for whole fields on the farm (Table 3). No fertilizer applications were included for perennials because yields reflect non-fertilized plots; also, observations from the whole-farm indicated that fertilizer was only needed in fields where seed harvest occurred. However, it is possible that fertilizer applications would be needed in later years with repeated biomass-only harvest. Costs and fuel use associated with these operations were estimated using agricultural engineering estimates of machinery operating costs and typical fuel use for field operations (Lazarus, 2014).

Table 3. Assumed management for assessment of perennial grass and forb production and corn production.					
Crop	Seedbed preparation	Planting	Weed control	Fertilizer	Harvest and post-establishment years
Perennial grass and forbs	Spray soybean stubble.	Double disk drill.	Mow twice.	None.	Spot-spray 2.5% of area; self-propelled mower-conditioner; baler; move bales to field edge using tractor with loader attachment.
Corn	Chisel plow; field cultivator.	Row crop planter; starter fertilizer: 22 pounds P/ acre and 10 pounds N/ acre.	Two herbicide applications.	120 pounds N/ acre using anhydrous applicator.	Combine with corn head used for grain harvest.

We assumed corn grain yields at the midslope were equal to the Moody County, SD average from 2009 to 2013, which was 162.5 bushels/acre (NASS, 2015). Yields at the shoulder (170 bushels/acre) and footslope (139.5 bushels//acre) were adjusted proportionally, based on yield measurements taken at the experimental site (Schumacher, 2011). Corn price was based on 2009 to 2013 average prices ($5.03/bushel) received by South Dakota farmers (NASS, 2015), with the high ($6.72/bushel) and low ($3.23/bushel) annual prices during this period used to illustrate potential ranges.

RESULTS OF ANALYSIS BY LANDSCAPE POSITION

Biomass production tended to be greater in plots with greater amounts of warm season grasses, regardless of landscape position. As a result, these mixtures had lower breakeven prices (Figure 25). Growing the appropriate warm season grass at each landscape position, rather than growing switchgrass monocultures, would reduce by 22 to 36% the price needed for biomass production to be as profitable as corn.

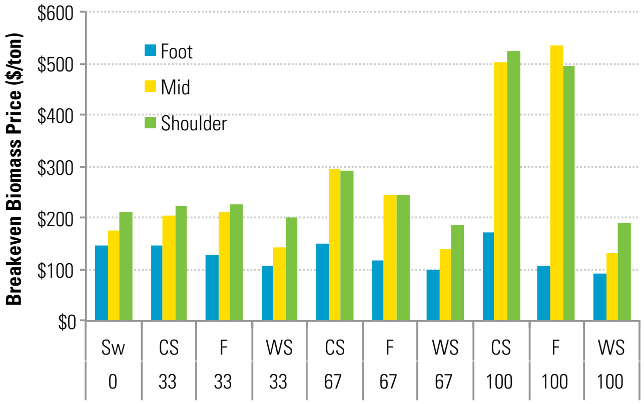


Figure 25. Breakeven farm-gate biomass price for biomass harvest to be as profitable as corn production for different switchgrass binary mixtures at three landscape positions (Sw=switchgrass, CS=cool season, F=forb, WS=warm season; companion crop portion of mixture 0, 33, 67, 100%; Thus, Sw 0 is a switchgrass monoculture, and WS 100 contains no switchgrass, only the companion warm season grass.).

A prairie cordgrass monoculture grown at the footslope produced the least expensive biomass. Similarly, least greenhouse gas emissions (Figure 26) and energy use (Figure 27) occurred for mixtures with high percentages of companion warm season grasses (100% at the footslope and midslope positions, 67% at the shoulder). Thus, growing the warm season species appropriate for each landscape position could reduce greenhouse gas emissions and energy use required for feedstock production by 4 to 21%, relative to switchgrass monocultures.

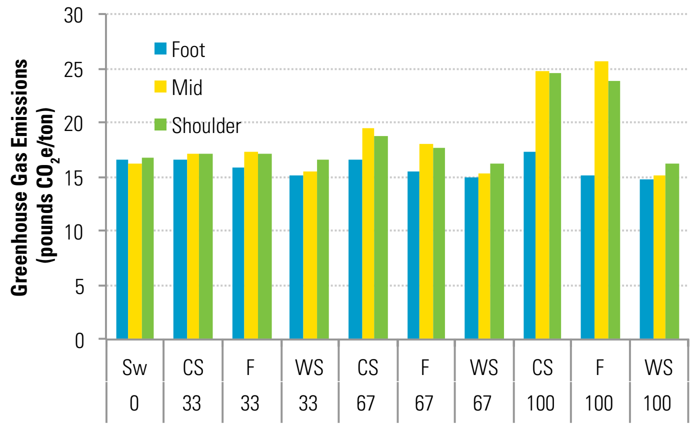


Figure 26. Greenhouse gas emissions in producing biomass for different switchgrass binary mixtures at three landscape positions. (Sw=switchgrass, CS=cool season, F=forb, WS=warm season; companion crop portion of mixture 0, 33, 67, 100%).

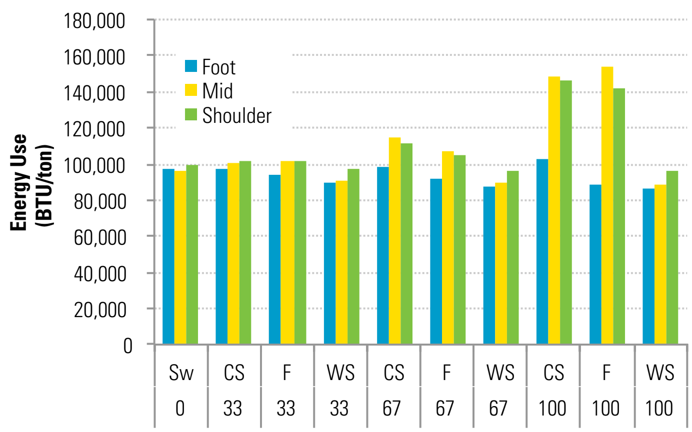


Figure 27. Energy use in producing biomass for different switchgrass binary mixtures at three landscape positions. (Sw=switchgrass, CS=cool season, F=forb, WS=warm season; companion crop portion of mixture 0, 33, 67, 100%).

Chapter 8
Conclusions

1. Productive grassland composed of native prairie plant species, valuable for both commercial (seed, hay, grazing, potential biofuel feedstock) and environmental (wildlife, soil health, biodiversity) purposes was quickly (two years) and successfully established on retired cropland using common farm equipment.

2. Agricultural soils contained abundant and diverse populations of weed seeds that required considerable effort and cost to control in grassland plantings. However, weed pressure declined over time as the grassland established.

3. Both mixtures and monocultures of selected prairie species were productive. Switchgrass monocultures generally outyielded mixtures; however, simple mixtures of species, strategically located on the landscape where they were best adapted, could outyield switchgrass and enhance biodiversity.

4. Ecosystem services "kicked in" almost immediately. Most noticeable was the rapid colonization of the restored grassland by wildlife, including migratory waterfowl, songbirds, amphibians, and insect pollinators. Soil health began to improve within a few years of being in grass, but further improvement could be made with more time.

5. Although not measured on our farm, other research has shown that re-establishing perennial vegetation dramatically changes the farm water budget. Less water runs off to reduce stream and river flooding downstream and more water percolates deeper into soil to supply plant growth and to recharge local aquifers. In addition, the lower fertilizer requirement for native grassland, and the rapid sequestering of available nutrients into organic matter by perennial grasses, reduces nutrient pollution into waterways (especially nitrate) compared to annual crop farming.

6. Restoring the water regime and vegetation of previously drained and farmed wetlands contributed significantly to farm income, primarily through the sale of wetland seed. The economic return per acre was often higher for restored wetlands than for upland grassland.

7. Once prairie species were established, income from approximately 500 acres used to produce native grass seed, hay, and grass-finished beef was similar to the median South Dakota household income. However, income was less than what could have been received by the farmer from land rent for row crop farming.

8. The farm produced ecosystem services (such as wildlife habitat and soil protection) for the public, but was mostly unable to financially profit from providing said services. Widespread adoption of farming perennial prairie species on prime cropland may require the public to pay for ecosystem services provided by such farms. If land was converted from farm program crops to perennial grass, the farm program subsidies might be used to pay for ecosystem services on the same acres without increased cost to taxpayers.

9. Biofuels currently are not produced at the commercial scale from native grasslands or from planted grasslands composed of native species, as was the case for the Prairie Farm. This seven-year experiment generated considerable quantitative data on the production, management, and marketing of biomass feedstock to inform a nascent cellulosic biofuel industry should one develop in the near future.

Chapter 9

Outreach, Publications, and Funding Sources

DOCUMENTARY FILM

Grass Roots: The Prairie Farm Story (40 minutes runtime). Available at: http://www.thegrassrootsfilm.com/

POST-DOCTORAL RESEARCHERS

Chang Oh Hong and Cody Zilverberg.

GRADUATE STUDENTS & GRADUATE THESES

Teoh, K.H. 2015. Improving ecosystem services and yield of bioenergy feedstocks through topographically matched polycultures. MS thesis. South Dakota State University, Brookings, SD.

Bourlion, N. 2012. Private and public benefits of innovative mix crop systems intended for biofuels production in eastern South Dakota. MS thesis. South Dakota State University, Brookings, SD.

Simon, B. 2012. Prairie wedgegrass: life history and potential for wetland restoration. South Dakota State University. Brookings, SD.

Heimerl, R.K. 2011. Comparisons of soil within a till plain across contrasting land uses. MS Thesis. South Dakota State University.

Vahyala, I.E. 2011. Soil structure changes in bioenergy crop management systems. Ph.D. Dissertation, South Dakota State University. Brookings, SD.

Erickson, L. thesis in preparation.

UNDERGRADUATE STUDENT WORKERS

Erin Beck, Nathan Ulmer, Levi Waddell, Levi Ringquist, Michael Mulvey, Charles Brunel, Seth Owens, Alan Mayer, and Ben Stout. The EcoSun Prairie Farm was also the central subject of Erin Beck's undergraduate honors project, "EcoSun Prairie Farms in Retrospect: Assessing a Sustainable Grass Farm Model" (May 2015).

FARM TOURS (SAMPLE OF THE MANY TOURS PROVIDED)

28 Aug. 2014. Farm tour with Jeff Oien, Tatanka Wetland Bank, Crooks, SD.

2 Aug. 2014. Farm tour with farmers from Willow Creek Farm, Heron Lake, Minnesota.

17 Oct. 2013. Farm tour with Dr. Craig Spencer and ecology class from Augustana College.

23 Sept. 2013. Farm tour with Dr. Carol Johnston and Wetland Ecology class from SDSU.

6 Sept. 2013. Farm tour with woman farmer's group from Nebraska.

20 Oct. 2013. Agricultural economics class led by Dr. Mike Miller from SDSU.

26 July 2013. Focused field tour open to invited stakeholders.

24 June 2013. Farm tour with Dr. Craig Spencer and an ecology class from Augustana College.

2 Oct. 2012. Farm tour with Dr. Mike Miller and economics class from SDSU.

20 Sept. 2012. Grassland ecology class (OLLI organization) led by Dr. Larry Tieszen (EROS and Augustana College).

3 Aug. 2012. Economics of grass farming. Public field tour.

9 July 2012. Farm tour with Dr. Meghann Jarchow, USD.

2 May 2012. Farm tour with staff from non-point source program SD DENR.

10 Oct. 2011. Farm tour with staff from POET.

15 Aug. 2011. Julia Ness of Land Stewardship Project and America's Grasslands: Status, Threats and Opportunities Conference.

1 Aug. 2011. Farm tour with 20 students from Virginia Tech.

15 July 2011. Public field tour.

2 Nov. 2010. Farm tour with Chris Misar, Graduate Student, SDSU.

26 Oct. 2010. Farm tour with staff from Millborn Seed Co.

16 Aug. 2010. Prairie establishment for biofuels and wildlife. Public field tour.

8 Oct. 2009. Farm tour with Jerry Wilson, writer, SD Magazine.

20 Aug. 2009. Farm tour with Kurt Spence.

19 Aug. 2009. Farm tour with Todd Mortenson (SD rancher).

24 July 2009. Farm tour with Dr. Meghann Jarchow, current faculty member and sustainability program director, University of South Dakota, Vermillion.

3 June 2009. Field tour with Dr. Laura Jackson, current Director of the Tall Grass Prairie Center, UNI. Cedar Falls, IA.

30 Sept. 2009. Agriculture for a changing environment: discussion of carbon and energy enterprise and research in agriculture.

PEER-REVIEWED PUBLICATIONS

Zilverberg, C.J., K. Teoh, A. Boe, W.C. Johnson, and V. Owens. 2016. Strategic use of native species on environmental gradients increases diversity and biomass relative to switchgrass monocultures. Agriculture, Ecosystems and Environment 215:110-121.

Schumacher, T, A Eynard, R Chintala. 2015. Rapid cost-effective analysis of microbial activity in soils using modified fluorescein diacetate method. Environmental Science and Pollution Research 22:4759-4762.

Olson, K.R., A.N. Gennadiyev, R.G. Kovach, and T.E. Schumacher. 2014. Comparison of prairie and eroded agricultural lands on soil organic carbon retention (South Dakota). Open Journal of Soil Science 4:136-150.

Zilverberg, C., W.C. Johnson, D. Archer, S. Kronberg, T. Schumacher, A. Boe, and C. Novotny. 2014. Profitable prairie restoration: the EcoSun Prairie Farm experiment. Journal of Soil and Water Conservation 69:22A-25A.

Zilverberg, C.J., W.C. Johnson, A. Boe, V. Owens, D. Archer, C. Novotny, M. Volke, and B. Werner. 2014. Growing *Spartina pectinata* in previously farmed prairie wetlands for economic and ecological benefits. Wetlands 34:853-864.

Zilverberg, C.J., W.C. Johnson, V. Owens, A. Boe, T. Schumacher, K. Reitsma, C.O. Hong, C. Novotny, M. Volke, and B. Werner. 2014. Biomass yield from planted mixtures and monocultures of native prairie vegetation across a heterogeneous farm landscape. Agriculture, Ecosystems, and Environment 186:148-159.

BOOK CHAPTERS

Kiniry, J.R., M.N. Meki, T.E. Schumacher, C.J. Zilverberg, F.B. Fritschi, and V.G. Kakani. 2014. Modeling to evaluate and manage water and environmental sustainability of bioenergy crops in the U.S. in Advances in Agricultural Systems Modeling 5: Practical Applications of Agricultural System Models to Optimize the Use of Limited Water. Ahuja et al., ed. ASA, CSSA, SSSA. pages 139:160.

Reitsma, K.D., R. K. Heimerl, and T.E. Schumacher. 2011. Estimating Soil Productivity and Energy Efficiency Using the USDA Websoil Survey, Soil Productivity Index Calculator, and Biofuel Energy Systems Simulator. Pp. 425 – 443, In Clay, D.E. and J. F. Shanahan (eds.) GIS Applications in Agriculture, Volume 2; Nutrient Management for Improved Energy Efficiency. CRC Press, Boca Raton.

OTHER PUBLICATIONS

Brule, J. February 26, 2014. TEDx Brookings reinvents rural. Collegian. (Carter Johnson was one of the speakers of the first TEDx event in Brookings).

Zilverberg, C. 2013. The Prairie Farm: bringing back grass. Grassroots 15(2):2. March 2013.

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APPENDIX

Figure A1. Soils map of the EcoSun Prairie Farm (Soil Survey Staff, 2015). Satellite image was taken on 6 Oct., 2010.

Soil types on the Prairie Farm. Except for "% of farm," values in this table are published by the Natural Resource Conservation Service (Soil Survey Staff, 2015).			
Map unit symbol	Soil type	% of farm	Prime farmland?
Ba	Baltic silty clay loam	15	no
Bb	Baltic silty clay loam, ponded	< 1	no
Ca	Chancellor silty clay loam	< 1	if drained
DnB	Dempster-Talmo complex, 2 to 9 percent slopes	< 1	no
EeB	Egan-Ethan complex, 2 to 6 percent slopes	17	yes
ErD	Ethan-Clarno loams, 6 to 25 percent slopes	< 1	no
EtC	Ethan-Egan complex, 5 to 9 percent slopes	6	no
WcA	Wentworth-Chancellor-Wakonda silty clay loams, 0 to 2 percent slopes	5	if drained
WeB	Wentworth-Egan silty clay loams, 2 to 6 percent slopes	50	yes
WhA	Wentworth-Trent silty clay loams, 0 to 2 percent slopes	2	yes
Wo	Worthing silty clay loam	3	no

Table A1. List of the native plant species included in field restorations. Adapted from Zilverberg et al. (2014b).

Species			% of seed mix, by weight					
			Field					
Latin name	Common name	Variety	T1	T2[c]	T3	T4	T5	T6
Andropogon gerardii	Big bluestem	Sunnyview/Bonilla[a]		71		50	38	
Sorghastrum nutans	Indiangrass	Tomahawk		8		10	8	
Panicum virgatum	Switchgrass	Nebraska 28[b]	100	7	100[b]	9	4	100[b]
Schizachyrium scoparium	Little bluestem	Badlands		6		20	2	
Rudbeckia hirta	Blackeyed susan	IA native		1			<1	
Astragalus canadensis	Canada milkvetch	MN native		1			3	
Heliopsis helianthoides	Smooth oxeye	NA		1				
Ratibida pinnata	Pinnate prairie coneflower	NA		1				
Amorpha canescens	Leadplant	SD native		<1			<1	
Ratibida columnifera	Upright prairie coneflower	NA		1				
Echinacea spp.	Echinacea	NA		1				
Dalea candida	White prairie clover	MN native		1			2	
Dalea purpurea	Purple prairie clover	MN native		1			3	
Sporobolus asper	Tall dropseed	IA native					2	
Elymus canadensis	Canada wildrye	Mandan					2	
Bouteloua curtipendula	Sideoats grama	Butte				10	2	
Nasella viridula	Green needlegrass	Lodorm					7	
Agropyron trachycaulum	Slender wheatgrass	Revenue					7	
Pascopyrum smithii	Western wheatgrass	Rosana					16	
Desmanthus illinoensis	Illinois bundleflower	IA native					2	
Helianthus maximilliani	Maximillian sunflower	Medicine Creek					<1	
Silphium perfoliatum	Cup plant	WI native					<1	
Silphium integrifolium	Rosinweed	IA native					<1	
Silphium laciniatum	Compassplant	IA native					<1	
Aster laevis	Blue aster	MN native					<1	
Liatris pycnostachya	Prairie blazing star	IA native					<1	
Solidago rigida	Stiff goldenrod	IA native					<1	
Zizia aptera	Meadow zizia	IA native					<1	

[a] Big bluestem variety in fields T4 & T5 was Sunnyview, others were Bonilla.
[b] Field T3 was planted to 'Sunburst' switchgrass, and field T6 to 'Summer' switchgrass.
[c] Replicated experiments 1 and 2 were planted to the T2 mix.

Table A2. Percentage of quadrats that contained at least one plant of the listed species in field T2 in 2014, as influenced by slope. The entire field was planted to the same mixture of 13 species.

Slope (feet / foot)	< 0.03	0.03 to 0.06	0.06 to 0.09	> 0.09
Number of quadrats	12	31	12	6
Species				
Big bluestem	100	100	100	100
Indiangrass	83	90	100	100
Little bluestem	33	32	50	67
Sideoats grama	0	3	0	0
Switchgrass	25	35	33	33
Native C4 grass total	100	100	100	100
Native C3 grass total	0	0	0	0
Purple prairie clover	0	16	8	33
White prairie clover	0	23	42	17
Canada milkvetch	0	13	8	0
Smooth oxeye	8	0	0	0
Native forb total	8	29	42	33
Canada thistle	67	55	8	33
Yellow/white sweetclover	8	9	25	50
Exotic forb total	83	61	33	67

Table A3. Percentage of quadrats that contained at least one plant of the listed species in field T5 in 2014, as influenced by slope. The entire field was planted to the same mixture of 24 species.

Slope (feet / foot)	< 0.03	0.03 to 0.06	0.06 to 0.09	> 0.09
Number of quadrats	10	21	18	9
Species				
Big bluestem	100	100	100	100
Indiangrass	100	100	83	89
Little bluestem	70	71	72	89
Sideoats grama	60	57	44	89
Switchgrass	40	71	39	56
Native C4 grass total	100	100	100	100
Slender wheatgrass	50	95	78	67
Western wheatgrass	80	90	83	78
Canada wildrye	30	24	56	22
Green needlegrass	10	5	6	0
Native C3 grass total	90	95	100	89
Purple prairie clover	90	95	100	100
White prairie clover	100	95	94	100
Canada milkvetch	50	38	17	11
Pinnate prairie coneflower	10	5	0	0
Maximillian sunflower	20	33	17	33
Blackeyed susan	20	10	6	0
Illinois bundleflower	0	5	6	0
Native forb total	100	100	100	100
Canada thistle	40	38	28	22
Dandelion	0	5	0	0
Exotic forb total	40	43	28	22

ECOSUN PRAIRIE FARMS

NEW RELEASE

PRAIRIE FARM CORDGRASS

Marketed exclusively by Millborn Seed Company
Brookings, SD

Prairie cordgrass is a native grass known as ripgut, slough grass, and marsh grass. Its competitive nature and tolerance to flooding and alkalinity make it a highly desirable species to plant on low ground where it can outcompete undesirable plants, including thistles.

Habitat/Distribution

Prairie cordgrass grows naturally in shallow wetlands and on sub-irrigated ground, tolerating both spring flooding and late summer drought. It thrives on marginal land between crops and more permanent wetlands. Cordgrass is found in a wide variety of climatic conditions throughout the Great Plains in the U. S. and Canada.

Availability

This is the first commercial offering of "Prairie Farm" cordgrass. The seed source is from a natural population in south-eastern SD. It is produced only on the EcoSun Prairie Farm.

Prairie Farm Cordgrass at EcoSun Farm

New Release

Description

Prairie cordgrass is a perennial grass that regrows from thick rootstocks each year. It reaches 10 feet tall, including flowering stalks. It is strongly rhizomatous, spreading rapidly and forming thick swards. Its dark-green color turns to yellow-gold in the fall. About 175,000 seeds weigh one pound.

Use

Prairie cordgrass grows where upland-adapted plants cannot survive. It provides incomparable year-round habitat for wildlife because it greens up early and its robust stems resist lodging from heavy rain and blowing snow. If harvested early, cordgrass makes fair-quality hay. Because it produces up to 10 tons of dry matter/acre, it has high potential as a biofuel feedstock.

Establishment

Prairie cordgrass can be established by planting greenhouse plugs or sowing seed in the spring or by drilling into dry ground in the late summer or fall.

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In SD, this variety produces more biomass, grows taller, and is less susceptible to rust than "Red River" cordgrass.

Figure A2. Prairie cordgrass flier.

Prairie Farm Wedgegrass

Introduction

Prairie wedgegrass (*Sphenopholis obtusata*) is an important native wetland plant species. Its role as an early successional colonizer of disturbed habitat enables it to compete well with invasive and undesirable species and to provide wildlife habitat and soil stability.

Habitat/Distribution

Prairie wedgegrass grows in sub-irrigated conditions, low-prairies, wet-meadows, marshes, stream banks, shores, dunes, moist woods, and waste places, at 0–8000 ft above sea level. Its geographic range extends from Canada through most of the United States, Mexico, and the Caribbean. Prairie wedgegrass is common but often overlooked because it rarely grows in dense stands.

Description

Prairie wedgegrass is a cool season annual or short-lived perennial. Its stems are tufted to solitary, 20-130 cm tall; sheaths glabrous or hairy; ligules 1.5-2.5 mm, erose-ciliate, more or less lacerate; blades 5-14 cm long, 2-8 mm wide, usually flat; panicles 5-15 cm long, 0.5-2 cm wide, usually erect, often spikelike; spikelets densely arranged, 2.2-3.6 mm long, 2-3 flowered; glumes strongly dimorphic in size and shape, first glume is shorter and less than 1/3 as wide as the second glume, the second glume is subcucullate (wedge shaped) with a rounded to truncate apex. Wedge grass flowers from late June to August.

Use

Prairie wedgegrass is recommended for use in native wetland seed mixes for wetland restorations, riparian buffers, stream bank stabilization, and roadside restoration. Wedgegrass can provide wildlife habitat, stabilization of disturbed areas, and act as a nurse crop for more permanent native vegetation. Prairie wedgegrass is reported to have good forage value.

Establishment

Prairie wedgegrass is easy to establish, with few germination requirements. Wedgegrass can be drilled, broadcast, or plugged. Drilling wedgegrass with a no-till drill in early spring is especially effective. Natural seed fall from prairie wedgegrass forms a soil seed bank that enables it to regenerate quickly when soil moisture conditions are favorable.

Availability

This is the first commercial offering of prairie wedgegrass for wetland restoration use. The source for this seed is a natural population in eastern South Dakota near Colman. Seed under the trade name "Prairie Farm Wedgegrass" is produced only at the EcoSun Prairie Farm and is marketed exclusively by Millborn Seed Company in Brookings, SD.

Figure A3. Prairie wedgegrass flier.

Table A4. Harvest activities in fields on the EcoSun Prairie Farm.

Vegetation type	Field	Field size, acres	2008	2009	2010	2011	2012	2013	2014
'Nebraska 28' switchgrass	T1	39	established	none	seed	seed fall biomass	seed fall biomass	seed fall biomass	seed fall biomass
13-species bluestem mix	T2	40	established	none	summer biomass	grazed	grazed fall biomass	fall biomass	big bluestem seed fall biomass
'Prairie Farm' prairie cordgrass	T2	1.1	established	none	seed	seed	seed fall biomass (partial)	seed fall biomass (partial)	fall biomass
'Sunburst' switchgrass	T3	20	established	none	seed	seed fall biomass	seed fall biomass	seed fall biomass	seed fall biomass
5-species bluestem mix	T4	40		established	summer biomass	fall biomass	fall biomass	grazed	seed fall biomass
24-species bluestem mix	T5	113			established	summer biomass (partial) fall biomass (partial)	summer biomass (partial) fall biomass (partial)	fall biomass (partial)	fall biomass (partial)
'Summer' Switchgrass	T6	10			established	seed fall biomass	seed fall biomass	seed fall biomass	seed fall biomass
Remnant prairie seed mix	T7	39				established	none	none	seed (partial) fall biomass

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