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Biomass yield from planted mixtures and monocultures of native prairie vegetation across a heterogeneous farm landscape

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ABSTRACT

Farms in the glaciated tallgrass prairie region of North America are topographically heterogeneous with wide-ranging soil quality. This environmental heterogeneity may affect choice and placement of species planted for biomass production. We designed replicated experiments and monitored farm-scale production to evaluate the effects of landscape position, vegetation type, and year on yields of monocultures and mixtures. Research was conducted on a 262-ha South Dakota working farm where cropland had been replanted with a variety of native grassland types having biofuel feedstock potential. Vegetation type (diverse mixture or switchgrass [*Panicum virgatum* L.] monoculture) and year interacted to influence yield in replicated experiments ($p < 0.10$). Mean annual switchgrass yield above a stubble height of 10 cm was 9.3 Mg ha^{-1} in two replicated experiments, and was greater than yield of mixtures (7.3 Mg ha^{-1}) in 6 of 7 year × vegetation type combinations. Landscape position interacted with year and vegetation type to influence yield ($p < 0.10$). Variability was generally greatest at the lowest landscape position. On the farm's larger fields (0.4–46 ha), three-year mean yields of switchgrass monocultures cut at ground level (12.7 Mg ha^{-1}) were also greater than yields of mixtures (9.7 Mg ha^{-1}) but both were less than prairie cordgrass (*Spartina pectinata* Link) monoculture yield (13.2 Mg ha^{-1}) in a restored wetland. A combination of prairie monocultures and mixtures, strategically placed across a farm landscape, could offer a balance of productivity, ecosystem services, and income with potential as biofuel feedstock and other income streams (hay, seed, beef).

1. Introduction

Less than 4% of the North American tallgrass prairie remains (Samson and Knopf, 1994). Globally, savannas, shrublands, and temperate grasslands, like the tallgrass prairie, are the world's most at-risk biomes due to high rates of habitat conversion and low rates of habitat protection (Hoekstra et al., 2005). Most of the tallgrass prairie is privately owned and despite efforts by government agencies and not-for-profit organizations to protect or restore the prairie through acquisition of property or easements, the remaining tallgrass prairie continues to be destroyed because its fertile soils support high commodity crop yields in the Midwest and Northern Plains regions of the U.S. Recent spikes in the prices of corn (*Zea mays* L.) and soybeans (*Glycine max* L.) and the expiration of Conservation Reserve Program (CRP) contracts have encouraged further grassland conversion in recent years (Wright and Wimberly, 2013).

The CRP program has contributed to the conservation of soil resources and the establishment of grassland, but the program does have several weaknesses. First, privately-owned land enrolled in the CRP program cannot be harvested except when permitted by the government in response to a shortage of forage, as in the case of severe drought. This restriction generally precludes grazing by large herbivores, an historic aspect of prairies, and it reduces the land's economic value to the landowner and greater society. Second, the recent loss of previously restored grassland is a weakness of temporary easements like those of the CRP that cannot guarantee long-term restoration. Finally, reductions in government spending threaten the viability of continuing CRP and similar conservation programs at historic levels.

An alternative to purchasing land or easements and prohibiting agricultural activities is to promote the restoration and management of privately owned tallgrass prairie as working lands that remain in agricultural production but are managed according to

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sound ecological principles. The idea is not new; it is essentially the "land ethic" proposed by Leopold (1949). Nevertheless, there remains a need to investigate and promote the economic value of tallgrass prairie to support and encourage landowners who desire to improve their land management by increasing the portion of their acreage allocated to perennial grassland. Potential income streams from restored grassland include grazing, forage, biofuel feedstock, native seed production, hunting rights, ecotourism, and carbon credits.

The emerging biofuels market is an attractive option for marketing prairie plants. The U.S. government's renewable fuel standard mandates increasing production of cellulosic ethanol (EISA, 2007). Cellulosic feedstock can also be used to produce energy via alternative technologies, such as synfuel. Regardless of the conversion process, producing biomass for biofuels rather than animal feed offers several advantages. First, unlike forage production, high N concentrations are not desirable for biofuel feedstock (Sanderson et al., 1999). This enables delaying harvest until later in the season when nutrients have been translocated from leaves and shoots to roots, reducing nutrient export and the need for fertilization. Second, later harvests increase the value of the grassland for wildlife, especially during the nesting season for resident and migratory birds. Harvest can even be delayed until the following spring for maximum wildlife benefit, but with some yield loss. Third, biomass harvests provide an alternative market for perennial grasses for those land managers who do not want to manage grazing animals.

The future biofuels market, when combined with other potential income streams, may offer an opportunity to simultaneously practice ecological conservation, keep prime farmland in agricultural production, and reduce our nation's reliance on foreign, unstable, or less efficient sources of energy. A drawback of producing biofuel feedstock is that, at present, little demand exists because there are few refineries in production that convert prairie grasses to biofuels. This problem is mitigated by the similarities in the production of hay and cellulosic biofuel feedstock; until a stable cellulosic feedstock market emerges, a manager could produce late-season hay for the low- to mid-quality hay market.

Switchgrass (*Panicum virgatum* L.) has been identified as a leading candidate for high-yielding biofuel feedstock production in monoculture plantings (Sanderson and Adler, 2008). Although switchgrass is a perennial native of the tallgrass prairie that would provide improved ecosystem services relative to annual crops, monocultures lack the diversity valued for prairie restoration and wildlife habitat (Howe, 1994; Robertson et al., 2011). In addition, some research has shown increasing diversity increases yield and resilience (Tilman et al., 2001; Peterson et al., 1998), but others have found diversity did not increase yield (e.g., Johnson et al., 2010; Sanderson et al., 2004). Diverse prairie biomass plantings will often be preferred to monocultures if yield is maintained at or near monoculture levels, but if not, mixtures may still be preferred when a suite of ecosystem services is desired (Sanderson et al., 2004).

This research focuses on the biomass production of restored prairie planted on retired cropland and CRP on the EcoSun Prairie Farm, established in 2008 on 262 ha in extreme eastern South Dakota. EcoSun's objectives were to demonstrate and conduct research on the establishment and management of native prairie plants on a commercial farm, while enhancing ecosystem goods and services and generating revenue to support a farm family. EcoSun's priority ecosystem services include: improved wildlife habitat, vegetation diversity, reduced soil erosion, soil C sequestration, increased water retention via wetland restoration and perennial groundcover, and improved surface and groundwater quality.

At the start, EcoSun anticipated producing feedstock for a local (∼15 km distance) ethanol refinery. When the refinery did not purchase cellulosic materials as anticipated, we sought alternative biomass markets. Nevertheless, EcoSun remains prepared to produce biofuel feedstock to contribute to the U.S.'s national goal of 61 billion L of cellulosic ethanol by 2022 (EISA, 2007) and to instruct other potential producers how to establish biofuel feedstocks. To date, the farm's actual revenue streams have included sale of hay and seed from native plants as well as grazing fees and marketing of beef from grass-finished cattle (*Bos taurus*). Dormant-season hay produced on the farm could be used for cellulosic biofuel feedstock, if the price for feedstock was competitive with the price of hay. Alternative income streams for cellulosic biofuel feedstock may remain important in the future because they could stabilize farm economics during periods of low energy prices.

We collected farm-scale and small plot data on the Prairie Farm. Farm-scale data are real-world production values in a case study format. An advantage of the case study approach is that results incorporate the realistic challenges not faced by research conducted on a smaller scale. For instance, actual farm fields contain high heterogeneity such as wet and dry spots, topographic variation, animal damage to crops and soil, and more difficult weed control compared to homogeneous soils on small, manicured plots. These challenges impact yield projections when scaling-up from small plot research to farm- and field-scale. Advantages of smaller plot research are that treatments can be replicated and conditions like soil variation can be controlled to answer very specific questions.

The EcoSun Prairie Farm combined the case-study and small plot approaches with data collection on a single farm, to capitalize on the advantages of both. Research at the farm addressed two main questions: (1) What biomass and seed yield levels can native prairie plants produce on previously-tilled farmland?, and (2) Are diverse mixtures of prairie grasses as productive as switchgrass monocultures?

2. Materials and methods

2.1. Site description

The research farm was located in the North American tallgrass prairie and the prairie pothole region near Colman, SD (44.029, −96.850). Soils were predominantly silty clay loams, two-thirds of which were considered "prime" farmland (Tables 1 and 2). The farm was in MLRA 102c, where approximately 74% of the land is cropland. Mean annual precipitation was 686 mm (Table 3).

2.2. Establishment and management

Prior to establishment of perennial grasses, the farm had been in a corn-soybean rotation typical of the region. Establishment of individual fields occurred in stages beginning in 2008 (Table 4 and Fig. 1); the last field-scale planting occurred in 2011 (Table 5). Species and varieties used in mixtures (Table 6) were required to meet three criteria to achieve goals: (1) be historic components of tallgrass prairie vegetation, (2) be locally-adapted, and (3) be commercially available. These criteria allowed for the creation of diverse mixtures of tallgrass prairie plants, some tailored to specific income streams, while permitting replicability by agricultural producers. A 3-m Truax grass drill (Truax Company; New Hope, MN) was used for seeding. All herbicide application except spot-spraying was done using a 3780-L Blumhardt sprayer with an 18-m boom. Periodic fertilization of switchgrass fields is anticipated in the future to maintain seed yields. However, from restoration through 2012, no fertilizer was applied to any field to discourage weeds from competing with native C4 grasses (Berg, 1995; Rothrock and Squiers, 2003; Doll et al., 2011) and to comply with

Table 1
Major soil types on the Prairie Farm, and soil types included in replicated experiments. Except for "% of farm," values in this table are published by the Natural Resource Conservation Service (Soil Survey Staff, 2013).

Soil type	% of farm	Prime farmland?	Crop productivity index	Range production (Mg ha^{-1})		
				Favorable year	Normal year	Unfavorable year
Baltic silty clay loam	14.8	No	34	8.6	7.5	6.4
Dempster-Talmo complex, 2–9 percent slopes	0.5	No	49	4.7	3.7	2.7
Egan-Ethan complex, 2–6 percent slopes	17.5	Yes	79	5.3	4.2	3.1
Ethan-Egan complex, 5–9 percent slopes	5.7	No	64	5.1	4.1	2.9
Wentworth-Chancellor-Wakonda silty clay loams, 0–2 percent slopes	5.1	If drained	83	6.0	4.9	3.8
Wentworth-Egan silty clay loams, 2–6 percent slopes	49.4	Yes	86	5.4	4.3	3.2

Table 2
Components of major soil map units on the Prairie Farm. Numbers are the percentages that each component contributes to the major map units.

Components of major soil map units	Taxonomic classification	Major soil map unit					
		Baltic silty clay loam	Dempster-Talmo complex	Egan-Ethan complex	Ethan-Egan complex	Wentworth-Chancellor-Wakonda silty clay loams	Wentworth-Egan silty clay loams
Baltic, undrained	Fine, montmorillonitic (calcareous), mesic Cumulic Vertic Endoaquolls	85					
Chancellor	Fine, montmorillonitic, mesic Vertic Argiaquolls	3		2	2	20	1
Lamo	Fine-silty, mixed (calcareous), mesic Cumulic Endoaquolls	3					
Salmo	Fine-silty, mixed (calcareous), mesic Cumulic Endoaquolls	3					
Wakonda	Fine-silty, mixed, mesic Aquic Calciustolls	3		2	4	15	2
Arlo, undrained	Fine-loamy over sandy or sandy-skeletal, mesic Typic Calciaquolls	3					
Dempster	Fine-silty over sandy or sandy skeletal, mixed, mesic Udic Haplustolls		55				
Talmo	Sandy-skeletal, mixed, mesic Udorthentic Haplustolls		25		1		
Houdek	Fine-loamy, mixed, mesic typic Argiustolls		6				
Kranzburg	Fine-silty, mixed, frigid Udic Haploborolls		6				
Doland	Fine-loamy, mixed, frigid Udic Haploborolls		4				
Graceville	Fine-silty, mixed, mesic Pachic Haplustolls		4				
Egan	Fine-silty, mixed, mesic Udic Haplustolls			60	40		30
Ethan	Fine-loamy, mixed, mesic Typic Calciustolls			25	45		2
Trent	Fine-silty, mixed, mesic Pachic Haplustolls			9	7		9
Worthing	Fine, montmorillonitic, mesic Vertic Argiaquolls			2	1	10	1
Wentworth	Fine-silty, mixed, mesic Udic Haplustolls					55	55

Table 3
Precipitation (mm) at the Flandreau, SD weather station, approximately 25 km from the research site (NOAA, 2013).

Year	Annual	April–September	June–September
2008	735	485	309
2009	580	341	270
2010	1002	848	745
2011	764	636	401
2012	672	476	120[a]
30-yr mean	686	522	369

[a] Lowest since records began in 1893.

our objective of being a low-input system. Within fields T2 and T4 (Fig. 1), 3-m × 135-m strips were drilled with 'Sunburst' switchgrass (Boe and Ross, 1998) monocultures at 10 kg PLS ha^{-1} at the same time that the rest of the fields were drilled. Strips were used to make within-field comparisons of yield differences between switchgrass monocultures and species mixtures.

Throughout the farm, wetlands were restored by installing ditch plugs or berms to stop drainage that was previously encouraged in order to expand cultivation onto low ground. Two seasonal wetlands of 0.5 and 0.6 ha within field T2 were not planted to the grass-forb mixture, but were instead plugged with prairie cordgrass (*Spartina pectinata* Link) plants raised from seed in a greenhouse. A 1.4-ha wetland in field T5 was also restored as part of a replicated experiment by transplanting plugs and drilling seed of prairie cordgrass. Smaller wetlands and waterways throughout the farm were

Table 4
Prairie Farm land area (ha) by usage. Values are the number of ha in each land-use category in the current year. Thus, each column sums to the total farm size, 262 ha, except for small differences due to rounding. Fields undergoing restoration were considered to be in the "establishment phase" until the year they were first harvested.

Land use	2008	2009	2010	2011	2012
Mixed species restoration	0	16	29	72	72
Renovated CRP	0	0	6	17	17
Switchgrass monoculture	0	21	21	24	24
Restored wetland	0	2	4	15	15
Non-native cool-season grass pasture	33	33	33	33	33
CRP/wetland not renovated	41	41	41	41	41
Restoration in establishment phase	65	40	69	22	22
Annual cropland	114	99	50	27	27
Farmstead	9	9	9	9	9

restored by planting them with prairie cordgrass and other native plants that have commercial value.

Beginning in their second year, switchgrass monoculture fields (T1, T3, T6) were harvested annually for seed production after a killing frost. Residue was baled in 2011 and 2012. Mixed species

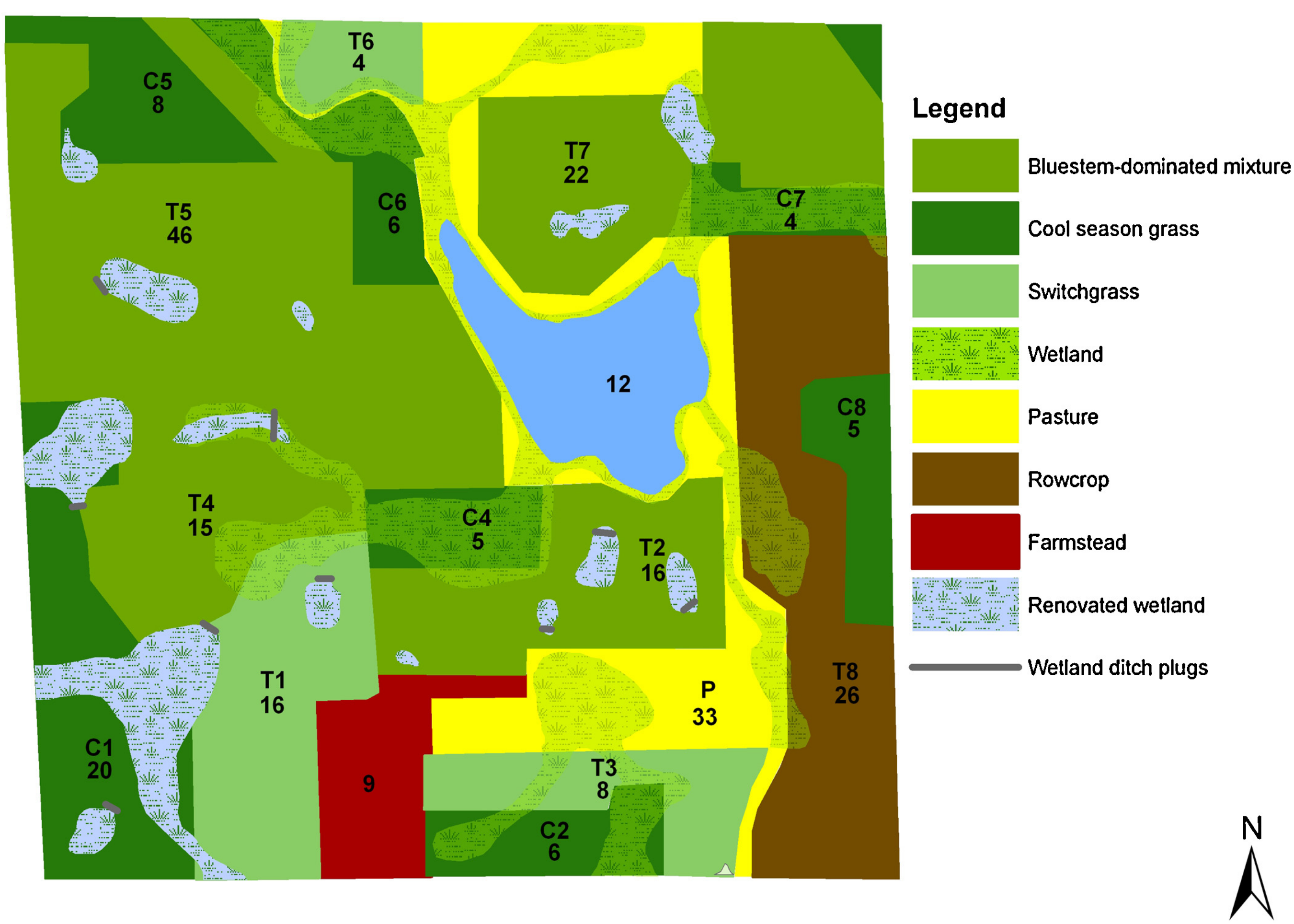

Fig. 1. The EcoSun Prairie Farm in 2012. Fields previously in the Conservation Reserve Program (CRP) are labeled with a "C". Fields labeled beginning with a "T" were in a corn–soybean rotation when restoration began in 2008. Exotic cool-season pasture is labeled "P". Below field name labels are field areas, in ha.

Table 5
Details of establishment and weed control of fields on the EcoSun Prairie Farm[a,b].

Field	Seed source	Establishment year (year 1)	Post-establishment management
T1	'Nebraska 28' switchgrass (Alderson and Sharp, 1994)	2008; preplant: Plateau (imazapic) & glyphosate; seeding date: 9–17 June; mowed to control pigweed (*Amaranthus* spp.)	Year 2: Paramount (quinclorac) and Milestone (aminopyralid) Year 3: spring burn; Paramount; 0.2 ha spot-sprayed w/glyphosate to control cool-season grasses Year 4: spring burn Year 5: spring burn
T2	Mixture of forbs and warm-season grasses (Table 6)	2008; preplant: Plateau and glyphosate; seeding date: 12–14 June; mowed to control pigweed	Year 2: 4 ha spot-sprayed w/Milestone to control Canada thistle (*Cirsium arvense* [L.] Scop) and musk thistle (*Carduus nutans* L.); mowed to control Canada thistle; spot-mowed bull thistle (*Cirsium vulgare* [Savi] Ten.) Year 3: spring burn; Milestone on 6 ha to control Canada thistle and sowthistle (*Sonchus* spp.) Year 4: spot-spray Milestone to control Canada thistle and sowthistle Year 5: spring burn; spot-sprayed w/glyphosate to control cool-season grasses; spot-spray Milestone to control Canada thistle; mowed 4 ha to prevent Canada thistle from going to seed
T3	'Sunburst' switchgrass	Same as T1	Year 2: Paramount and Milestone; ~2 ha redrilled because of poor establishment Year 3: spring burn; 0.2 ha spot-sprayed w/glyphosate to control cool-season grasses Year 4: spring burn Year 5: spring burn
T4	Warm-season grass mixture (Table 6)	2009; preplant: Plateau; seeding date: 28 April; mowed twice	Year 2: half of field sprayed w/Milestone to control pigweed, Canada thistle, and sowthistle Year 3: no herbicide applied Year 4: 0.2 ha spot-sprayed w/glyphosate to control cool-season grasses
T5	Mixture of forbs, cool-, and warm-season grasses (Table 6)	2010; preplant: Plateau; seeding date: 9–12 April; spot-sprayed w/Milestone to control Canada thistle and musk thistle; mowed twice	Year 2: spot-sprayed w/Milestone; spot-mowed to control thistle
T6	'Summer' switchgrass	2010; preplant: Plateau; seeding date: 12–13 April; spot-mowed to control weeds; winter broadcast seed in areas of poor initial establishment	Year 2: Milestone to control sowthistle Year 3: spring burn; 0.2 ha spot-sprayed w/glyphosate to control cool-season grasses; 0.2 ha spot-sprayed w/Milestone to control Canada thistle
T7	Diverse mixture from seed harvested from a remnant prairie	2011; seeding date: 1 Dec 2010; mowed 3 times to control weeds	Year 2: spot-sprayed w/glyphosate

[a] Seeding rate was 10 kg PLS ha^{-1} for all fields except T7, which was planted with bulk seed.
[b] Chemical application rates were as follows, except where noted otherwise: Plateau: 0.04 L a.i. ha^{-1} for switchgrass monocultures and 0.07 L a.i. ha^{-1} for all others; glyphosate: 1.91 L a.i. ha^{-1} with 0.25% surfactant; Paramount 0.45 L a.i. ha^{-1}; Milestone 0.15 L a.i. ha^{-1}; spot-spraying of glyphosate was with a 2% glyphosate mixture.

plantings (T2, T4, T5) were hayed and/or grazed each year after the establishment year. Most haying occurred after a killing frost, but a small amount of hay was harvested earlier (early July) to obtain higher quality forage. Field T7, planted by snow-seeding in Dec. 2010 with seed harvested from a high-diversity virgin prairie owned by The Nature Conservancy, was not yet in commercial production in 2012.

2.3. Data collection

Cordgrass was sampled using 1.0-m^2 quadrats; all other fields were sampled with 0.5-m^2 quadrats. Samples were collected at ground level with a rice knife, bound, removed from the site, and air-dried to constant weight before recording weights. The number of yearly samples collected per treatment varied with field size and field variability, ranging from 5 to 63 with a mean of 22. From 2009 to 2011, a subset of samples were reweighed after the bottom 15 cm of the sample was removed. The mean percentage of remaining biomass (83%) was used to estimate biomass that could be harvested at a 15-cm stubble height. The percentage of ground covered by canopy of non-crop plants was visually estimated before cutting most quadrats.

Seed of switchgrass and prairie cordgrass monocultures was harvested with a John Deere 3300 combine, and yields of pure live seed (PLS) were determined by commercial businesses. Commercial field-scale equipment (swather-windrower and large round baler) were used to harvest biomass from entire fields after hand-cut samples were taken. Field equipment left a stubble height of approximately 12 cm. Bales were weighed by trailer load in autumn 2011 (462 kg $bale^{-1}$), autumn 2012 (601 kg $bale^{-1}$), and summer 2012 (588 kg $bale^{-1}$). The number of bales from each field were counted and all bales were assumed to have the same weight in a given season and year, except for prairie cordgrass, which was weighed separately in 2012 (659 kg $bale^{-1}$). The same equipment was used to make large round bales in summer 2010, summer 2011, and autumn 2011, so all were assumed to weigh the same (462 kg $bale^{-1}$). Small square bales made in 2010 were assumed to weigh 34 kg.

2.4. Yield projections

We estimated potential biomass production for the entire farm under 3 scenarios, assuming all arable land was dedicated to biomass production. All land that was cultivated in 2008, when

Table 6
Native plant species included in field restorations.

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

[a] Source of seed classified as a cultivar (C), selected (S), or native (N).
[b] Big bluestem source in fields T4 & T5 was Sunnyview, others were Bonilla.
[c] Field T3 was planted to 'Sunburst' switchgrass, and field T6 to 'Summer' switchgrass.

restoration began, and most of the land in CRP was considered arable, for a total of 177 ha on the 262-ha farm. Scenario #1, "Full production", assumed the current proportion of switchgrass monocultures (17%), mixtures (79%), and prairie cordgrass monocultures (3%) would be scaled-up to all cultivable land. Scenario #2 assumed all cultivable land would be planted to mixtures, and scenario #3 assumed all cultivable land would be planted to switchgrass monocultures.

Projected yields assumed use of field-scale hay-making equipment. For each scenario, a value was estimated for potential production at 2011 yield levels, when the farm had the highest biomass production ha^{-1}, and at 2012 yield levels, when the farm had the lowest biomass production ha^{-1}. These two years were chosen to give the widest range of observed yields. Dormant hay yields for 2012 were 5.8 Mg ha^{-1} (switchgrass), 4.2 Mg ha^{-1} (mixtures), and 8.3 Mg ha^{-1} (prairie cordgrass). Yield projections for 2011 were calculated using multipliers based on the difference between biomass of hand-clipped plots between 2011 and 2012. Multipliers for switchgrass, mixtures, and prairie cordgrass were 1.3, 1.7, and 1.1, respectively. These multipliers were applied to 2012 field-scale yields. Autumn-harvested yields of switchgrass and cordgrass were, on average, 59% of the yields cut by hand at ground level in 2012. In contrast, fields of bluestem mixtures, which were not harvested for seed before being baled, yielded 64% of hand-cut mixtures. We attributed the difference between 59 and 64% as loss due to seed harvest. Seed itself was less than 5% of total biomass, but some stem and leaf were not harvestable by the baler after fields were harvested for seed. For yield projections, we assumed no seed would be harvested prior to biomass harvest, so switchgrass and prairie cordgrass projections were increased by 5% to account for loss due to seed harvest.

Net revenue for the projected yield was estimated using a value of \$100 Mg^{-1} for hay, which was intermediate between prices actually received on the farm in 2011 and 2012. We assumed the cost of producing hay or corn was \$173 or \$1112 ha^{-1}, respectively, without land rent, interest, or insurance. To calculate the corn price at which hay and corn would produce equivalent net revenue, we assumed a corn yield of 10 Mg ha^{-1}, which was the mean 2011 yield in Moody County, SD (NASS, 2013).

2.5. Replicated experiment 1

Experiment 1 was located within field T1, described above. Soils were Wentworth-Egan silty clay loams with 2 to 6 percent slopes. Three landscape positions (summit, backslope, and footslope) were identified on three different slopes within the field. At each landscape position, two plots of perennial vegetation were planted: 'Sunburst' switchgrass at 11 kg PLS ha^{-1} and a big bluestem-dominated mixture of prairie species (Table 6) at 10 kg PLS ha^{-1} on 2 June 2008. Plot sizes were 9 m × 1.8 m. Mean slope length was 90 m. No fertilizer was applied. The field was sprayed with Plateau (imazapic, 0.04 L a.i. ha^{-1}) and glyphosate (1.91 L a.i. ha^{-1} with 0.25% surfactant) prior to seeding. In subsequent years, plots were spot-sprayed with Milestone (aminopyralid; 0.15 L a.i. ha^{-1}) to control Canada thistle (*Cirsium arvense* [L.] Scop). Plots were sampled by randomly placing two (in 2009) or three (2010–2011) quadrats within each plot in autumn 2009–2011 (mean date: 22 Oct.) and summer in 2009 and 2010 (mean date: 18 Aug.). Areas harvested in summer were avoided when harvesting in autumn. Quadrat size was 0.19 m^2. All standing biomass within quadrats was cut with a rice knife at 10 cm and air dried to a constant weight before recording weights. Plots were burned in spring 2010 and

2011. The experiment was statistically analyzed as a randomized block design with slopes as blocks, vegetation type was the main plot factor, landscape position was the subplot factor, and year was a repeated measure. An α level of 0.10 was used.

2.6. Replicated experiment 2

Experiment 2 included six blocks in a completely randomized block design on land that had previously been in a corn-soybean rotation. Blocks were assigned according to differences in soil type and aspect. Relatively productive Wentworth and Egan upland soils were found in half of the blocks, whereas the other half included Dempster and Talmo soils, which have lower water-holding capacities and productivity (Table 1). Lower parts of the landscape were dominated by Worthing and Baltic soils that are poorly drained, associated with temporary wetlands, and prone to spring flooding. Vegetation type was the main plot factor, with two levels: switchgrass, or a big bluestem-dominated mixture of native warm-season grasses and forbs (Table 6). Seeding rates, species, and varieties were the same as replicated experiment 1. Planting was approximately perpendicular to the contour, such that each vegetation type extended from the summit to the footslope, a distance of ~60 m. No fertilizer was applied. Plots were spot-sprayed with Milestone (0.15 L a.i. ha^{-1}) to control Canada thistle. Plots were sampled by collecting biomass at three landscape positions: summit, backslope, and footslope. Perennial grasses were cut along the contour with a BCS sickle-bar mower (99-cm and 114-cm models, Harvard, MA 01451) that left a 10-cm stubble height. Therefore, sampling area varied with mower used and width of the plot, which ranged from 7 to 9 m. Biomass was weighed in the field; subsamples were air dried, weighed, and used to adjust wet weights to a dry matter basis. All reported values were on a dry matter basis. After weighing, one half of each vegetation type had its residue removed, so that main plots were split into two subplots: residue removed and residue retained.

Data from experiment 2 were analyzed as a randomized complete block design with vegetation type in the main plot, residue treatment in the subplot, landscape position in the sub-subplot, and year as a repeated measure. All possible interactions were included. Analysis of variance indicated no significant effect of residue treatment or any interaction including residue treatment. Therefore, data were aggregated by residue treatment and the analysis was rerun without the effect of residue. Mean separation was carried out when F-tests indicated an effect was significant. An α level of 0.10 was used unless otherwise indicated. Coefficients of variation were calculated for each combination of vegetation type × landscape position × year.

3. Results

3.1. Replicated experiment 1

For summer harvest of experiment 1, the only significant effect was vegetation type (Table 7); switchgrass biomass (14.3 Mg ha^{-1}) was greater than the bluestem-dominated mixture (10.0 Mg ha^{-1}). Summer yields were 108 and 103% of autumn yields for switchgrass and the mixture, respectively. In autumn, switchgrass biomass was numerically greater than the bluestem mixture from 2009 to 2011, but the yield difference declined each year and was not significant in 2011 (Table 8). Likewise, switchgrass biomass was numerically greater than bluestem mixture biomass at all landscape positions, but the difference was only significant at the summit. Switchgrass yields were greater at the summit than backslope or footslope, but bluestem mixture yields did not differ across landscape positions. The two vegetation types had similar coefficients of variation (CV) at most landscape × year combinations (Table 9). The greatest mean CV for both vegetation types occurred at the footslope.

Table 7
Significance (p-values) of main effects and interactions in the replicated experiments.

Factor	Experiment 1 – autumn	Experiment 1 – summer	Experiment 2 – autumn
Vegetation	0.07	0.05	<0.001
Position	0.20	0.12	<0.001
Year	0.05	0.80	<0.001
V × P	0.09	0.29	0.64
V × Y	0.07	0.92	0.03
P × Y	0.22	0.80	0.01
V × P × Y	0.32	0.74	0.64

3.2. Replicated experiment 2

In experiment 2, two interactions were significant: position × year and crop × year (Table 7). Switchgrass biomass exceeded biomass of the bluestem mixture in all years (Table 10). Yield was numerically greater at the backslope position than the summit or footslope in all years, but differences among location were not always significant in the first two years (2008–2009). Biomass of perennial grasses increased each year. The CV for switchgrass was less than or equal to the coefficient of variation for the bluestem mixture in all but 1 of the 12 landscape position × year combinations (Table 9). The CV at the footslope was higher than other landscape positions in the establishment year, but was similar to other positions in subsequent years.

3.3. Field- and farm-scale

Visual estimates of non-crop ground cover from 2010 to 2012 averaged 2% for bluestem, 5% for switchgrass, and 25% for prairie cordgrass. Most non-crop plants in prairie cordgrass plantings were native wetland species found in the understory of the much taller prairie cordgrass, and were not removed because they added diversity and were not strongly competitive with cordgrass. One exception was river bull rush (*Schoenoplectus fluviatilis* [Torr.] M.T. Strong), which was a strong competitor in the central, deeper portions of the wetlands. All five of the C4 grasses planted in field T4 were found in sampling quadrats in 2012 (Table 11). Big bluestem and Indian grass combined for 68% groundcover in T4. Thirteen of the 24 species planted into field T5 were identified in sampling quadrats, and we observed three more of the planted species at other times. Together, three species (big bluestem, Indian grass, and slender wheatgrass) provided 60% groundcover in T5.

Autumn-harvested biomass, cut by hand at ground level, increased from 2009 to 2011 in response to maturation of stands and above-average precipitation (Table 12 and Fig. 2). Switchgrass outyielded bluestem mixtures in most fields and years. Prairie cordgrass established more slowly than switchgrass, but prairie cordgrass yields equaled or exceeded switchgrass yields by the third growing season. From 2009 to 2012, bluestem mixtures yielded 24% less than switchgrass monocultures. The bottom 15-cm of samples cut at ground level contained 17% of total biomass. Yields obtained using field-scale harvesting equipment (Table 13) were less than yields obtained by hand. In 2012, field scale harvests were 64% of hand harvests for bluestem mixtures (fields T4 & T5), 60% for prairie cordgrass (wetland in field T2), and 58% for switchgrass (Field T1). Hayed area increased each year as additional land came into production and a market for post-seed-harvest switchgrass residue was found. In 2012, 73 of the 129 ha of restored land were hayed. Of this area, 25 ha were harvested for seed prior to haying and 12 ha were grazed before or after haying. The remaining 56 ha of restored land, 33 ha cool season pasture, and 31 ha non-restored former CRP were grazed but not hayed in 2012. Mean switchgrass seed yield from 2010 to 2012 was 193 Mg ha^{-1} (Table 14).

We projected yields of autumn-harvested biomass if all arable land (177 ha) on the farm was dedicated to producing biofuel feedstock (Fig. 3). In a year with

Table 8
Biomass yields (Mg ha^{-1}) of switchgrass and a bluestem-dominated mixture at three landscape positions in replicated experiment 1. Values are means of three blocks averaged across year or landscape position. Within a column, values followed by the same lowercase letter are not significantly different at $p = 0.10$. Within a row, values followed by the same capital letter are not significantly different at $p = 0.10$.

Vegetation	Year			Mean	CV	Landscape position		
	2009	2010	2011			Summit	Backslope	Footslope
Bluestem mix	9.5a	10.0a	13.0a	10.8	0.17	10.5aZ	10.6aZ	11.3aZ
Switchgrass	13.5b	12.9b	13.4a	13.3	0.02	15.5bZ	12.3aY	12.1aY

Table 9
Mean annual coefficients of variation in replicated experiments for two vegetation types and three landscape positions. Soils in experiment 1 were more productive than in experiment 2.

	Switchgrass			Bluestem mix		
	Summit	Backslope	Footslope	Summit	Backslope	Footslope
Experiment 1						
3-yr mean (2009–2012)	0.16	0.17	0.25	0.18	0.10	0.20
Experiment 2						
2008	0.31	0.34	0.63	0.43	0.37	0.92
3-yr mean (2009–2012)	0.21	0.20	0.19	0.29	0.27	0.31

Table 10
Biomass yields (Mg ha^{-1}) of switchgrass and a bluestem-dominated mixture at three landscape positions in replicated experiment 2. Values are means of six blocks averaged across residue treatments and position or perennial species. Species or landscape position within a column followed by the same letter are not statistically different ($p > 0.10$).

Species	Year				Mean (09–11)	CV
	2008	2009	2010	2011		
Bluestem mix	2.0a	2.3a	3.6a	5.2a	3.7	0.39
Switchgrass	2.6b	3.7b	5.8b	6.5b	5.3	0.27
Landscape position	Switchgrass & bluestem mix				Mean (09–11)	CV
	2008	2009	2010	2011		
Summit	2.4ab	3.1a	4.3a	4.6a	4.0	0.20
Backslope	2.7a	3.2a	5.4b	6.8b	5.1	0.35
Footslope	1.8b	2.7a	4.4a	5.8c	4.3	0.36

Table 11
Visual estimates of ground cover (%) in fields T5 and T4 in 2012, by species.

Species	Field	
	T5	T4
Big bluestem	27	56
Indiangrass	15	12
Switchgrass	2	6
Little bluestem	2	5
Canada wildrye	3	
Sideoats grama	2	1
Slender wheatgrass	18	
Western wheatgrass	4	
Canada milkvetch	1	
White prairie clover	2	
Purple prairie clover	3	
Illinois bundleflower	0.1	
Maximillian sunflower	0.3	
Weeds	3	2
Total	82	81

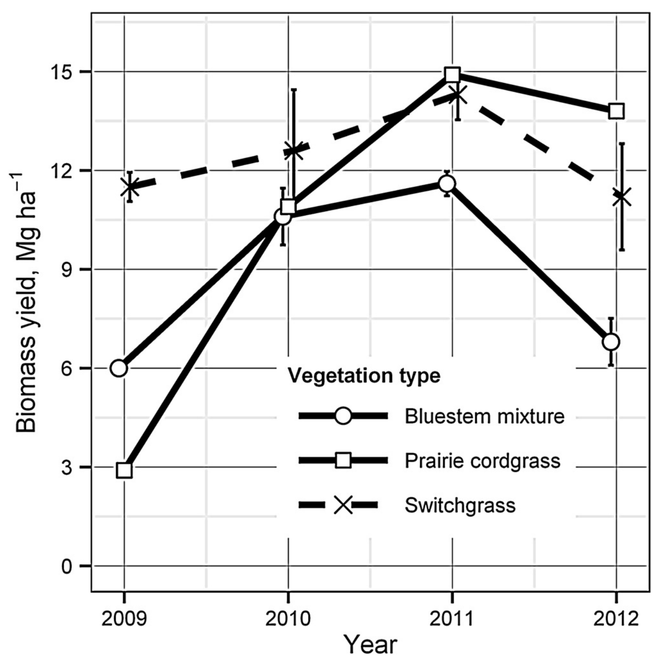

Fig. 2. Biomass yield of three vegetation types on the Prairie Farm, harvested by hand at ground level. Each point represents the mean of all established fields in a given year. Vertical lines represent ± the standard error when more than one field was sampled.

sub-optimal but favorable growing conditions (2011), we projected 1297 Mg could have been produced using the current allocation among switchgrass and prairie cordgrass monocultures and species mixtures. At this yield, gross revenue for the farm would be $129,700. Hay and corn would have produced equivalent net revenue at a corn price of $165 Mg^{-1}. Planting all arable land to switchgrass monocultures would have resulted in 1375 Mg, whereas planting species mixtures would have yielded 1267 Mg.

4. Discussion

4.1. Yield

Mixtures of native tallgrass prairie species, of which switchgrass was a minor component, consistently yielded less than switchgrass monocultures. This result occurred in two replicated experiments, in samples taken from fields including three different prairie mixtures, and when using field-scale harvesting equipment. In east-central Minnesota, Tilman et al. (2001) found that biomass yield increased with diversity, but DeHaan et al. (2010) found that simple mixtures yielded similarly to high-yielding diverse mixtures when they included a C4 grass and a legume. In contrast, at a site near our experiment, Hong et al. (2013) found increased diversity did not increase yield over switchgrass monocultures. In Iowa, Picasso et al. (2008) found that, although yields generally increased with increasing diversity, this was not necessarily true for high-yielding monocultures. Also in Iowa, Jarchow and Liebman (2012) found increasing the functional diversity of a C4 grass mixture by adding legumes and C3 grasses did not increase yield.

Johnson et al. (2010) found that when potential alfalfa biomass production was above the threshold of 3.2 Mg ha^{-1} in Nebraska, biomass production was greater for alfalfa monocultures than for

Table 12
Autumn-harvested biomass (Mg ha^{-1}) at the Prairie Farm, cut at ground level.

Species	Source	Field	Field size (ha)	Establishment	2009	2010	2011	2012	Comments
Bluestem mix		T1	Plot	2008	10.6[a]	11.2[a]	14.4[a]	6.6	Replicated experiment #1
Switchgrass	Sunburst	T1	Plot	2008	15.1[a]	14.4[a]	14.9[a]	8.5	Replicated experiment #1
Switchgrass	NE28	T1	15.8	2008	11.1	15.9	13.4	NA	
Bluestem mix		NA	Plot	2008	2.6[a]	4.0[a]	5.8[a]	NA	Replicated experiment #2
Switchgrass	Sunburst	NA	Plot	2008	4.1[a]	6.4[a]	7.2[a]	NA	Replicated experiment #2
Bluestem mix		T2	16.2	2008	6.0	9.8	11.8	Grazed	
Switchgrass	Sunburst	T2				9.1	Grazed	Grazed	Strip
Prairie cordgrass	Prairie Farm	T2	0.4	2008	2.9	10.9	14.9	13.8	
Switchgrass	Sunburst	T3	8.1	2008	12.0	15.7	14.1	14.1	
Bluestem mix		T4	16.2	2009		11.5	12.1	8.1	
Switchgrass	Sunburst	T4				9.8	16.6	11.1	Strip
Bluestem mix		T5	45.7	2010			10.9	5.6	
Switchgrass	Summer	T6	4.0	2010			13.4	NA	

[a] Plot experiments used a 10-cm cutting height from 2009 to 2011. Therefore, values from those experiments were multiplied by 1.115 to adjust to a ground-level cutting height for presentation in this table.

Table 13
Actual field-scale harvest of biomass (Mg ha^{-1}) at the Prairie Farm with large round or small square balers. Values are means of all fields, grouped by year, dominant species, and season of harvest. Switchgrass and prairie cordgrass fields were also harvested with a combine to collect seed; thus, biomass reported here was the residue remaining after seed harvest. Individual bluestem fields were not hayed more than once annually, but in 2010 and 2011, some bluestem fields were harvested in summer and others in autumn.

Year	Species	Season	Biomass (Mg ha^{-1})	Area hayed (ha)
2010	Bluestem mixture	Summer	4.9	23
2011	Bluestem mixture	Summer	4.5	8
2011	Bluestem & switchgrass[a]	Autumn	6.2	43
2012	Bluestem mixture	Summer	3.8	13
2012	Bluestem mixture	Autumn	4.2	36
2012	Switchgrass	Autumn	5.8	23
2012	Prairie cordgrass	Autumn	8.3	0.4

[a] Bluestem mixture and switchgrass bales were not measured separately in 2011.

Table 14
Seed yield from switchgrass monoculture fields.

Field	Yield (kg ha^{-1})		
	2010	2011	2012
T1	317	250	132
T3	285	234	230
T6	[a]	75	126

[a] Establishment year.

the native plant community. Potential biomass at our site was above this threshold (Table 1). Indeed, much of the farm was considered prime farmland and our yields of both mixtures and monocultures (Table 12) greatly exceeded the Natural Resource Conservation Service's potential range production (Table 1). In this setting, it may be difficult for diverse mixtures to outyield switchgrass monocultures. However, the literature and our own preliminary data suggest that strategic selection of species in simple mixtures, planted in landscape positions where they are well adapted, can maintain or exceed yield of switchgrass monocultures. Finally, although switchgrass monocultures generally outyielded mixtures in our experiments, this trend might be reversed over a longer time frame (Cardinale et al., 2007).

The yield difference between switchgrass monocultures and prairie mixtures varied with year and field. In general, switchgrass established more quickly than mixtures, so that differences between switchgrass and mixtures were greatest in the year after establishment and then persisted at lower magnitude. In the third to fifth years after establishment, yields of switchgrass typically exceeded mixtures by 1–3 Mg ha^{-1}, although there were instances where mixtures exceeded monocultures, or where monocultures greatly exceeded mixtures (>5 Mg ha^{-1} difference). When mixtures outperformed monocultures, it was due to poor performance of the monocultures rather than unusually high performance of mixtures.

One theorized benefit of diversity is increased stability (McCann, 2000), but in both of our replicated experiments yield variation, one measure of stability, was greater for the mixture than the switchgrass monoculture. Our field scale data do not allow for the same direct comparisons because of differences in soils and years measured from field to field, but clues can still be taken from the data. The summer of 2012 was the driest on record (NOAA, 2013), and the lack of moisture was reflected in below-average yields. Under these conditions, mixtures might be expected to perform well relative to high-yielding monocultures, but we found the opposite response—in 2012, yields of mixtures declined, on average, more than yields of switchgrass or prairie cordgrass monocultures. For prairie cordgrass, a wetland plant, the smaller-than-expected yield loss might be due to a downslope shifting of its zone of maximum production within the wetland basin during the drought year (unpublished data), compensating for low yields at high elevations with higher yields at lower elevations. For switchgrass, its performance during 2012 confirms the species' adaptation to a wide variety of conditions. It should also be noted that although the summer of 2012 was historically dry, above-normal precipitation occurred in May, which delayed the onset of moisture stress during the summer. Thus, more extreme moisture conditions are certainly possible in this region.

Yield variation was greater between the two replicated experiments than it was within either single experiment. Both experiments used the same species and varieties, were established

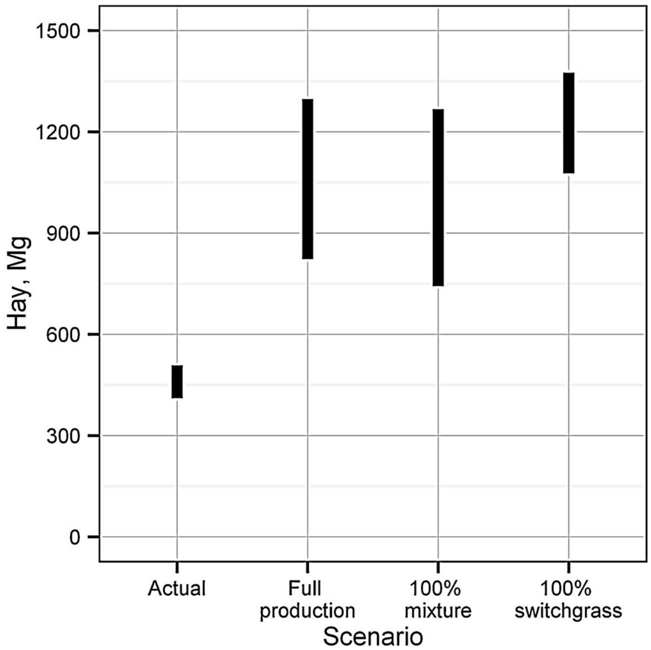

Fig. 3. Actual and projected annual yield scenarios for the Prairie Farm. Projections assume all cultivable land (177 of 262 ha) on the farm were converted to native grasses in equal proportions to the Actual situation ("Full production"; 79% of land in mixtures, 17% switchgrass monocultures, and 3% prairie cordgrass monocultures), or were converted to 100% switchgrass or 100% native species mixtures. Bars extend from 2012 yields (4.2, 5.8, and 8.3 Mg ha^{-1} for mixtures, switchgrass monocultures, and prairie cordgrass monocultures, respectively) at their low points to 2011 yields (7.2, 7.8, and 9.4 Mg ha^{-1} for mixtures, switchgrass monocultures, and prairie cordgrass monocultures, respectively) at their highest points. Less area was actually harvested in 2011 than 2012, which explains the small difference in actual total farm yield between years, compared to the larger difference between years in the projected scenarios.

at the same time, and were cut at the same stubble height from 2009 to 2011. Soil differences accounted for part of the yield difference. The two easternmost blocks of experiment 2 contained soils similar to those in experiment 1. These easternmost blocks yielded 27% more than other blocks in experiment 2 at the summit and backslope positions from 2009 to 2011. At the footslope there were no differences between east and west because soils were more similar across footslopes and eastern blocks were more prone to flooding. A second difference between the two experiments was that establishment in experiment 1 was observed to be more successful than in experiment 2. This observation was supported by the initially high and relatively consistent yields in experiment 1. In contrast, yields in experiment 2 started low and doubled from 2009 to 2011. Finally, mechanical cutting in experiment 2 likely contributed to some yield loss, relative to hand-clipping in experiment 1.

Landscape position affected mean yield in both replicated experiments, but perhaps more importantly, landscape position also affected yield variability. Variation was generally greatest at the lowest landscape position, the footslope. In experiment 2, two of the six footslopes were particularly prone to flooding or subirrigation. Yield of corn grain planted at these footslopes was diminished in wet years (Schumacher, 2011) and the resulting variability was reflected in a much higher CV for corn grain at the footslope position than for biomass yield of switchgrass or the bluestem mixture (data not shown).

4.2. Ecosystem services

Among the benefits provided by perennial rather than annual agriculture are hydrologic regulation and water purification, climate regulation, pest control, and improvement of soil quality and nutrient cycling (Asbjornsen et al., in press). Replacing row crops with perennial grasses benefits wildlife (Best et al., 1997). Perennials' deep roots and longer growing season can reduce loss of water and N moving through the soil profile (Randall et al., 1997). Perennials reduce soil erosion, improving the long-term sustainability of yields on cropland. Perennial vegetation can also improve soil quality by increasing soil organic C stocks of soils previously in annual crop production (e.g., McLauchlan et al., 2006; Baer et al., 2002), but the particular perennial species present may (McLauchlan et al., 2006) or may not (Knops and Tilman, 2000) affect C accumulation rate. Soil organic matter (SOM) in cropland at our site was much less (40–55% lower) than a nearby reference prairie (Heimerl, 2011), suggesting SOM and corresponding soil organic carbon (SOC) was depleted by decades of growing annual crops. This suggests that perennial native prairie grasses have the potential for improving soil over time, replacing much of the lost SOC.

Although there is an abundance of research showing ecological benefits of biodiversity in general, there is little specific information comparing the ecological benefits of switchgrass monocultures to more diverse prairie plantings. Among those studies comparing switchgrass monocultures to more diverse mixtures, floristic diversity was associated with arthropod (Robertson et al., 2012) and avian diversity (Robertson et al., 2011), although switchgrass monocultures can also provide quality habitat for many bird species (Robertson et al., 2013). Compared to reference grasslands across a wide geographic area, soils of switchgrass monocultures had similar microbial genetic diversity but lower microbial genetic abundance (Watrud et al., 2013). Polycultures typically face lower pest pressure than monocultures (Altieri, 1999), although controlling weeds with herbicides is easier for plantings of a single functional group. Including legumes in a mixture can reduce the need for industrially-produced N fertilizer (Jarchow and Liebman, 2012), and the concomitant release of CO_2 to the atmosphere. A variety of rooting architectures may allow mixtures to capture more soil nutrients (Postma and Lynch, 2012) and prevent their loss to the environment as pollutants. Finally, and perhaps most importantly, polycultures may be preferred for their ability to conserve the intrinsic value of diversity.

This research farm increased biodiversity at multiple spatial scales, relative to its previous cropping history. Planting a mixture of species into a field is one approach that, relative to monocultures, increases biodiversity at very small scales (<1 m^2) to very large scales (>100 ha). This approach was evaluated within the replicated experiments and on fields of 16 and 46 ha. An alternative approach operating at the field scale is to plant one or more monocultures within a larger field. This approach was used in fields T2 and T5, where restored wetlands were planted to prairie cordgrass, and on the margins of field T6, where both sides of a waterway were planted to prairie wedge grass (*Sphenopholis obtusata* [Michx.] Scribn.). Cordgrass and wedge grass were planted as monocultures in these areas to facilitate harvest of their seed. Both species were placed in environments where they would occur naturally (wetlands and the wetland-upland margin). Matching species with landscape position in this way works particularly well when the monoculture and the surrounding crop are both biomass crops that can be harvested after a killing frost, but they could also be compatible with other kinds of crops, including grain crops. For instance, prairie cordgrass could be planted into wetlands within annual crop fields to increase biodiversity, improve wildlife habitat, and provide revenue from a portion of a field that has low, variable yields of annual crops. On the Prairie Farm, cordgrass was grown primarily on Worthing and Baltic silty clay loam soils that are poorly drained, have slow permeability, and are unsuited for grain crop production, but have high potential biomass production (Table 1) for wetland-adapted species. Prairie cordgrass in the T2 wetland had similar biomass yields to switchgrass planted in other fields on the farm. Therefore, including prairie cordgrass in wetlands could increase field-scale biodiversity while maintaining high biomass yields.

Biodiversity at the farm- and landscape-scale were also increased. The patchwork of fields, wetlands, and waterways on the farm placed monocultures adjacent to mixtures and restored wetlands. Together, they were more diverse than the typical corn-soybean farm. The same was true at the landscape scale, where the Prairie Farm joined neighboring corn-soybean farms, an alfalfa field, and public wildlife production areas in a regional mosaic.

Some (e.g., Hill et al., 2006) have suggested targeting marginal lands for synfuel or cellulosic ethanol production because they have potentially higher net energy balances than corn- or soybean-based fuels and they would provide less competition with food crops grown on productive soils, like those of the historic tallgrass prairie. However, biofuel production on marginal lands would still compete with forage and livestock production (Sanderson and Adler, 2008). In addition, restoring or conserving only marginal lands will leave few opportunities for large, contiguous tracts of tallgrass prairie, and this historic ecosystem will remain in peril. A benefit of using restored land for biofuels in the tallgrass prairie region is that these rich soils could increase and stabilize biofuel feedstock production by achieving higher yields than the soils of marginal lands. Greater than 70% of the corn currently produced in the U.S. is used for ethanol or livestock feed (U.S. Grains Council, 2013), so converting some lands back to prairie for bioenergy and forage would produce materials with similar end use.

4.3. Production/restoration alternatives and economics

Conservation organizations, both private and public, have restored and protected many patches of native grassland in the U.S., including land owned by The Nature Conservancy that is just 3 km from the EcoSun Prairie Farm. As of October, 2013, the federal government's CRP program had 380,000 ha enrolled in the state of South Dakota (USDA, 2013). However, neither the land owned by the Nature Conservancy nor the land enrolled in CRP are typically managed for commercial production.

To our knowledge, there are no other large-scale attempts to return productive cropland to strategic mixtures of native prairie plants to generate sustainable commercial income through a variety of revenue streams. There are, however, examples of alternative approaches to improving ecosystem services and agricultural sustainability that share one or more attributes with the EcoSun Prairie Farm. For instance, some South Dakota landowners have restored former cropland to native vegetation for grazing and other ecosystem services (Boettcher and Johnson, 1997). Grazing native prairie remains common on land that is marginal for crop production in places such as western South Dakota and the Flint Hills of Kansas. The commercial hunting industry in South Dakota also provides an economic incentive for maintaining perennial vegetation as wildlife habitat. At the eastern edge of the tallgrass prairie, in Wisconsin, there is an initiative to replace some of the exotic cool season grasses typically used for grazing with native warm season grasses (Paine, 2013). In Iowa, the heart of U.S. corn and soybean production, researchers have advocated planting strips of native vegetation in water catchment areas that would compose 10–20% of cropland, as a way of restoring native vegetation and reducing pollution entering waterways (Hirsch et al., 2013). Researchers in the Southern High Plains of the U.S. have proposed returning farmland to commercial grassland as a response to declining irrigation water availability, but have placed more emphasis on exotic forage species than on native prairie species (Allen et al., 2012; Zilverberg et al., 2014, with editor). In Australia, creative management has included planting small grains in native grass pastures to generate more revenue from restored and existing grassland (White, 2013).

Other initiatives have focused on the planting of prairie species for use as bioenergy feedstock. For instance, Roeslein Alternative Energy aims to restore 12 million ha of prairie for bioenergy production in the U.S. MidWest—but, unlike EcoSun, Roeslein intends to target marginal lands (Roeslein Alternative Energy, 2013; Ripson, 2013) rather than productive cropland. In Wisconsin, private and public groups are collaborating in an effort to use biomass harvested from Waterfowl Production Areas for bioenergy (Williams et al., 2013).

To meet conservation and production objectives while reducing economic risk, the Prairie Farm employed enterprise diversification and sold several products: hay, seed, and beef, in addition to continued corn and soybean production on land not yet restored. In practice, hay, seed, and beef produced similar gross revenue. When yields were projected for scenarios that placed all arable land in hay production, potential production varied much more due to annual growing conditions than the type of feedstock (switchgrass or mixtures) produced (Fig. 3). The projected 2011 hay yield would have produced net revenue equivalent to corn at a corn price of \$165 Mg^{-1}. In South Dakota, the price of corn averaged \$239 Mg^{-1} from 2010 to 2012, but was just \$147 Mg^{-1} from 2007 to 2009 (NASS, 2013). Regardless of the crop planted on the arable area of the farm (177 ha), there were an additional 85 ha of land that could be put to other purposes, including a farmstead, grazing, or managed for wildlife habitat. If the land was owned, the net revenue (\$97,714) provided by the projected 2011 hay yield would have been much greater than the median household income (\$49,415) in South Dakota (U.S. Census Bureau, 2013).

The ecosystem services provided by polycultures are difficult to quantify, but the losses from lower yields are not. In 2012, the additional 1.9 $Mg\,ha^{-1}$ of hay harvested from switchgrass monocultures was worth ~\$190 ha^{-1}. This lost revenue would be difficult for many land managers to absorb. It may be possible to develop higher-yielding, more profitable mixtures than those used in this study. Alternatively, if society values the ecosystem services provided by polycultures, society could financially support polycultures' continued existence. There are many mechanisms that might achieve this, including government programs. However, given limited government budgets, it would be prudent to seek alternative mechanisms. One mechanism currently being explored by the Prairie Farm is marketing "prairie-raised beef" that was produced on restored polycultures. Consumers pay a premium for this local, high-quality product that achieves a social goal (prairie restoration). Perhaps consumers would also show a willingness to pay more for energy originating from local, restored prairies.

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