Wetlands
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ORIGINAL RESEARCH

Growing *Spartina pectinata* in Previously Farmed Prairie Wetlands for Economic and Ecological Benefits

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Abstract Wetlands in the Prairie Pothole Region of the U.S. are threatened by continued drainage and conversion to cropland. Commercial incentives may increase wetland restoration in lieu of easements. Therefore, we evaluated two commercially available populations of prairie cordgrass (*Spartina pectinata* Link) by comparing two planting techniques and identifying zones of maximum plant vigor and biomass production along a wetland-upland environmental gradient of a restored temporary wetland in east-central South Dakota. In the wetland center (maximum water depth: 0.4–0.5 m) plants were effectively established by transplanting, but not by drilling. Both techniques were effective above the wetland center. The zone of maximum vigor varied by year, ranging from the wetland bottom (0.5-m maximum water depth) to 0.25 m above the wetland-upland boundary. Biomass yield did not differ between populations but was affected by elevation. In a second experiment, 2 years after establishing plants by transplanting at 0.9- or 1.5-m spacing, biomass no longer differed between treatments. Our economic analysis indicated establishment costs could be recovered with < 10 years of biomass and seed harvests. Because prairie cordgrass can be established using conventional techniques and provides positive net revenue, it should be considered for incorporation into shallow wetlands in production fields.

Keywords Biomass · Biofuel · Wildlife · Establishment · Transplant · Agroecology · Conservation

Introduction

Wetlands are among the most transformed ecosystems on earth (Mitsch and Gosselink 2000; Batzer and Sharitz 2006). Wetland drainage, primarily by ditching and tiling, has expanded upland agriculture into low ground that was previously unsuitable due to flooding and sedimentation (van der Valk 2012). While expansion of cropland area into lowlands has had short-term economic benefits, losses of ecosystem goods and services in the form of biodiversity, fish and game habitat, flood attenuation, surface and ground water purification, stock watering, and carbon storage have been recognized and in some cases quantified (Galatowitsch 2012).

Wetlands in the American Midwest, including the Prairie Pothole Region of central North America, which was identified as a global conservation priority (Keddy et al. 2009), have been decimated by drainage for agriculture (Prince 1997). The subregions most favorable for agriculture had lost the large majority of their wetlands by the mid-20th century; currently, Iowa and western Minnesota have retained only several percent of their historic prairie wetlands, while drier areas farther west (the Dakotas) that are less suitable for grain production have retained about half of their historic wetlands (Dahl and

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Johnson 1991). Despite discovery of the benefits of wetlands to society and passage of federal protection laws in the United States, many of the few remaining wetlands and surrounding grasslands important for wildlife have recently been converted to farmland in response to record grain prices (Tiner 2009; Johnston 2013; Wright and Wimberly 2013).

While protection of the remaining wetlands must remain a high conservation priority, restoration is increasingly needed to recover lost ecosystem goods and services and to avoid extirpation and extinction of species. Prairie wetland restoration projects thus far have had limited success; function has been achieved more than biodiversity (Galatowitsch and van der Valk 1994; van der Valk 2012). Government organizations are common partners in restoration projects contributing funds, establishing policies, and passing laws; however, because of the "start-stop" nature of public funding, lack of policy continuity, and current budget crises, government support may be less assured in the future (Galatowitsch 2012).

An alternative approach to stimulate restoration has been adopted by EcoSun Prairie Farms, a non-profit South Dakota corporation. Their approach is to generate income from the sale of grassland products, including those from restored wetlands, to pay for the costs of restoration and to produce profitable farming operations based on perennial crops. More than a million farmed wetland basins in the eastern Dakotas currently under conservation easement protection by the U. S. Fish and Wildlife Service (Kurt Forman, personal communication, U.S. Fish and Wildlife Service) are potentially available for restoration and commercial production. These wetlands are often too wet to be planted to annual crops and, if planted, frequently yield poorly due to saturated soil conditions. If planted to perennial wetland plants with commercial value, they could be managed to regain some of the former goods and services lost by repeated tillage.

Fundamental to the success of this approach are the choices made among commercially-available species and ecotypes, identifying the optimal positioning of plants along environmental gradients, and determining effective methods of establishment on low, often wet, ground. Prairie cordgrass (*Spartina pectinata* Link; hereafter cordgrass) was one of the species chosen for planting experiments during the restoration of formerly drained shallow wetlands on EcoSun's "Prairie Farm." Cordgrass is native, vigorously competitive, often dominant in temporary and seasonal wetlands in the Prairie Pothole Region, and has commercial value as seed and biomass (hay and future biofuel feedstock) (Dix and Smeins 1967; Johnson et al. 1987; Boe and Lee 2007). Prairie cordgrass biomass yields of 14 Mg ha^{-1} measured on temporary wetlands on EcoSun's Prairie Farm were comparable to 'Sunburst', 'Summer', and 'NE28' switchgrass (*Panicum virgatum* L.) yields in nearby uplands on productive cropland soils (Zilverberg et al. 2014). Boe and Lee (2007) found during a 4-years experiment that cordgrass production exceeded that of switchgrass on well-drained farmland. Boe et al. (2009) noted the need for gradient studies to determine the optimal topographic and edaphic position for planting and growing cordgrass.

Cordgrass may be propagated by seed, or vegetatively by dividing and planting rhizomes. Fraser and Kindscher (2001) successfully transplanted cordgrass plugs from an existing wetland into an eastern Kansas floodplain using a tractor-mounted tree spade, but found that success was mediated by water depth. Though effective, transplanting plugs from existing wetlands is probably not practical for large scale plantings. Alternative methods of establishing cordgrass from seed must be found.

Little information exists for the cultivation of cordgrass. In addition, the Red River population was the only commercially-available seed (Jensen 2013) until the Prairie Farm population was released in 2011 by EcoSun Prairie Farms. Red River was released by the United State Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Plant Materials Center in Bismarck, North Dakota and is a composite of plants from eastern North Dakota, western Minnesota, and northeastern South Dakota (NRCS 2012). Because cordgrass is native to most of the United States, the small, northern geographic region from which Red River was selected leaves potential to make additional selections that might outperform Red River in other locations. The Prairie Farm population originated from seed collected from a natural population in the southeastern corner of South Dakota.

This paper reports on two experiments conducted at the EcoSun Prairie Farm: one compares vigor and biomass yield of the two populations of cordgrass for which seed was commercially available to determine how drilled seed or hand-planted plugs grown from seed in the greenhouse responded to a strong environmental gradient from wetland bottom to upland habitat. In a second experiment, we compared biomass of two transplant densities to determine how rapidly cordgrass spread vegetatively and filled interplant spaces in a temporary wetland.

Materials and Methods

Gradient Experiment

The research site was located at the EcoSun Prairie Farm near Colman, SD (44.029,−96.850). The experiment was conducted in a shallow basin (1.4 ha) classified as a temporary wetland (Stewart and Kantrud 1971) that typically fills up to a 50-cm depth with runoff in spring and dries out by midsummer. Wetland soils included Worthing (fine, montmorillonitic, mesic, Vertic Argiaquolls) in the basin, Chancellor (fine, montmorillonitic, mesic Vertic Argiaquolls) in the swale, and Wakonda (fine-silty, mixed, mesic Aquic Calciustolls) on the ridge surrounding the wetland, as inclusions in the soil association Wentworth-Chancellor-Wakonda silty clay loam with 0 to 2% slopes (NRCS 2011). Mean annual precipitation (1981 to 2010) at the Madison, SD weather station was 655 mm, with 495 mm from April to September (NOAA 2013). The wetland had been cultivated for annual crops for a century or more prior to its restoration by this experiment. In the year prior to planting, the field contained soybeans and post-harvest stubble remained at the time of planting cordgrass. Four sampling transects oriented northwest, northeast, southwest, and southeast were established in an "X" pattern in the wetland basin (Fig. 1). Transects began at the bottom of the basin and extended up the slopes beyond the 50-cm depth contour and into planted upland vegetation dominated by big bluestem (*Andropogon gerardii* Vitman). Different slopes in the four directions resulted in different transect lengths (57 to 83 m). Each transect was divided into two contiguous plots that were randomly assigned to planting type: drilling or plugging. Each plot was further divided into 2 subplots, each randomly assigned to a population: Red River or Prairie Farm.

Cordgrass plants of both populations were started from seed in cone-shaped containers ("cone-tainers"; Stuewe & Sons, Tangent, OR) in a greenhouse in the spring of 2010. Prairie Farm plugs were transplanted to the field on 26 May. Transplanting of Red River was delayed until mid-late June because of poor plant vigor due to growing conditions in the greenhouse. Each transplant subplot consisted of three rows, with inter- and intra-row plant spacing of 0.9 m. Drilled subplots also consisted of three rows, with two rows spaced at 0.8 m and two rows spaced at 0.6 m because of equipment restrictions. On 22 April 2010, both populations were planted using a 1.6-m wide Truax FLXII-88 grass drill (Truax Company; New Hope, MN) at a rate of 10 kg bulk seed ha^{-1} (7.5 kg PLS ha^{-1}). No herbicide or tillage was used throughout the experiment, but the wetland was mowed once above the grass height to control annual weeds during the establishment year.

Sampling occurred in October-November each year beginning in 2011, the second growing season, and continuing through 2013. Because of erratic establishment in some subplots, we visually determined which row of the three rows of each subplot had the most uniform stand from the center of the wetland to beyond the wetland-upland border, and used that row for all sampling except biomass. Plant height (distance from ground to top of natural leaf blade height), maximum inflorescence height (distance from ground to top of tallest inflorescence), and number of inflorescences were measured or counted within a 1 × 1 m quadrat at 2-m intervals along each transect from 2011 to 2013. Establishment success was defined as at least one cordgrass tiller within a sampling quadrat. A plant vigor index was created using the following equation:

$$\mathrm{Vigor} = [\mathrm{PH}/\max(\mathrm{PH}) + \mathrm{IH}/\max(\mathrm{IH}) + \mathrm{NI}/\max(\mathrm{NI})]/3$$

where PH is plant height, max(PH) is the maximum PH of any sample, IH is inflorescence height, max(IH) is the maximum IH of any sample, NI is the number of inflorescences m^{-2}, and max(NI) is the maximum NI of any sample.

Biomass sampling was conducted in 2013. For each transect, one point was randomly selected within each ~0.08-m change in elevation from 0 to 0.40 m elevation, and 2 additional points were randomly selected in the remaining, upper elevations. At each sampling point, all four treatments were sampled by cutting prairie cordgrass at ground level by hand with a curved, serrated blade (rice knife) within a 1.5 × 1.0-m

Fig. 1 *Left*, overhead image (to scale) of the experiment in a restored temporary wetland at the EcoSun Prairie Farm. *Right*, plot diagram showing layout of different treatments (not to scale)

quadrat (N=84). The quadrat was centered on the middle row of each treatment and the quadrat's width ensured that all three rows were sampled. Inter-row and inter-plant spaces had been filled in by new tillers, so that rows were no longer distinct from one another in many locations. Species other than prairie cordgrass were excluded from samples. In the wetland basin, the most common other species were river bulrush (*Schoenoplectus fluviatilis* [Torr.] M.T. Strong), dock (*Rumex maritimus* L.), cocklebur (*Xanthium strumarium* L.), and smartweed (*Polygonum coccineum* L.). In the uplands the most common species was big bluestem. Other species provided little ground cover except at elevation extremes where prairie cordgrass did not perform well. Biomass samples were weighed in the field. Subsamples were dried and weighed to estimate percentage dry matter. Elevation above the wetland bottom was measured at 2-m intervals along transects using conventional survey equipment.

A band of the wetland near the 0.5-m elevation contour was drilled with Prairie Farm at the same time experimental transects were established. The northern portion of this band was sampled in autumn 2011 by cutting at ground level within 1-m^2 quadrats (N=16). Results of this sampling were not statistically analyzed but are presented as yield estimates under larger-scale production. Yields from this band were representative of approximately 1/3 of the wetland where yields were greatest and therefore cannot be extrapolated to the entire 1.4-ha wetland.

Transplant Density Experiment

The transplant density experiment was located in two temporary wetlands ("eastern wetland" and "western wetland") on the same farm approximately 0.75 km southeast of the gradient experiment. Maximum water depth of both wetlands was approximately 0.4 m. Wetlands were 0.5 and 0.6 ha in size. The wetlands had been farmed in previous years with a corn (*Zea mays* L.)-soybean (*Glycine max* L. Merr.) rotation. They were prepared for planting by spraying glyphosate (N-[phosphonomethyl] glycine) at 4.7 L ha^{-1} on 21 May 2008. Prairie Farm cordgrass plants were started in the greenhouse and transplanted into the wetlands between 23 May and 10 July 2008. Each wetland was divided into two plots, one north and one south. Within each wetland, one plot was randomly assigned to each transplant density treatment (0.9- or 1.5-m spacing). In October 2008, transplant survival was determined for all plants and percentage success calculated. Wetlands were harvested for seed in the autumn of each year from 2009 to 2012. Post-harvest residue was left in the field except in 2011, when the eastern wetland (0.5 ha) was burned in autumn. In 2012, the western wetland was burned in the spring. Canada thistle (*Cirsium arvense* L.) was spot-sprayed with Milestone (2-pyridine carboxylic acid, 4-amino-3,6-dichloro-) as needed. Hybrid cattail (*Typha* X *glauca* Godr.) in the center of the wetlands was pulled by hand in May-June of 2011 and 2012.

Wetland biomass was determined by cutting samples at ground level with a rice knife in autumn before seed was harvested. In 2009, the year after establishment, individual plants were still discernible and were harvested individually. In subsequent years, plants had grown together, so all biomass within 1-m^2 quadrats, including plants other than prairie cordgrass, was harvested. Wetlands were divided into multiple zones of equal width, and one east–west sampling transect was randomly located within each zone. Each transect was further divided into subzones of equal width, and one sampling quadrat was randomly located within each subzone. The east wetland was sampled every year from 2009 to 2013. The west wetland was sampled in 2009 and 2011 only. A mean of 24 quadrats $wetland^{-1}$ $year^{-1}$ were collected, for a total of 165 samples.

Statistical Analysis of Gradient Experiment

Establishment success of all treatments was plotted against elevation. An elevational 'threshold' was visually identified at 0.1 m; below 0.1 m, success was low but above 0.1 m success was almost certain. Data were grouped by planting technique, population, elevation (above or below 0.1 m), and year, and percentage of successful sampling points was calculated. Red River transplant data were excluded from this analysis and all others because of poor vigor relative to Prairie Farm at transplanting.

For analysis of vigor, plant height, and inflorescence density, samples without a cordgrass plant were not included. Similarly, for analysis of maximum inflorescence height, samples without an inflorescence were not included. The loess function of R (R Core Team 2012) with a span parameter of 0.85 was used to draw smoothed lines with the local polynomial technique for each planting technique x population x year combination, plotted with vigor on the y-axis and elevation on the x-axis. After line estimation, vigor was aggregated by elevation groups of 0.05 m height before plotting points, to improve interpretation of graphs. Range of maximum vigor for each population x planting technique x year combination was calculated, with range of maximum vigor defined as the upper quartile of vigor values after taking the mean of values within elevation ranges of 0.05 m. When a value was in the upper quartile but was at least 0.10 m from the rest of the upper quartile points, it was considered an outlier and not included in the maximum vigor range.

Dependent variables plant height, inflorescence density, and maximum inflorescence height were evaluated using analysis of variance. The effect of population was determined for drilled plots, with a model including population in the main plot, elevation in the subplot, and year as repeated measure. Transect was considered a random blocking variable. The effect of planting technique was determined for the Prairie Farm population, using the same model except that planting technique replaced population in the main plot. For these analyses, elevation was treated as a categorical variable with four bins: 0 to 0.14, 0.15 to 0.44, 0.45 to 0.74, and 0.75 to 1.25 m. For bins containing more than one sampling point, means were calculated before analysis. Descriptive summary statistics were also calculated without aggregating into elevation bins.

Evaluation of the dependent variable biomass was also carried out using analysis of variance. The effect of population was determined for drilled plots, with a model including population in the main plot, elevation in the subplot, and transect as a random blocking variable. The effect of planting technique was determined for the Prairie Farm population, using the same model except that planting technique replaced population in the main plot. Elevation was a categorical variable with seven levels.

Fixed models were analyzed with the lm function of R (R Core Team 2012). Mixed model analyses from both experiments were carried out using the lme4 (Bates et al. 2012) and nlme (Pinheiro et al. 2012) packages of R. Statistical tests from both experiments were considered significant when $p <= 0.05$. All data plots were created with ggplot2 version 0.9.3 (Wickham 2009).

Statistical Analysis of Transplant Density Experiment

Years were analyzed independently because both wetlands were not sampled in all years. For years in which both wetlands were sampled, we used a mixed model with biomass as the dependent variable, wetland as a random effect, and spacing as a fixed effect. For years when only one wetland was sampled, there was no random effect in the model. Samples were considered pseudo-replicates.

Economic Analysis

A preliminary economic analysis was conducted to illustrate the potential revenue from a restored cordgrass wetland at the two transplant densities and direct seeding. Major costs included producing a plant for transplanting and transplanting into the field. Costs to produce a plant included labor to prepare soil and cones for planting, planting seeds, and daily watering. Other costs included greenhouse space rent, seed, potting soil, and cones. Cones were assumed to be reused for 5 years, so were annualized to a single year at $38.20 per thousand cones based on a purchase price of $170.00 per thousand cones and using an interest rate of 4 %. Based on actual labor used in producing plants for the transplant density study, total labor for producing the plants was estimated at 9.03 h per thousand plants, including 2.55 h for preparing soil and cones for planting, 5.46 h for planting seeds, and 1.02 h for checking and watering plants. A labor rate of $14.00 per hour (Lazarus 2013) was used for the analysis, so total labor cost was $126.40 per thousand plants. Greenhouse space rent was calculated using a rental cost of $4.31 m^{-2} of bench space per month and 3 months of use. Each cone rack was 0.186 m^2 and held 98 cones, so 1.9 m^2 bench space was used per thousand plants for total rent of $24.60 per thousand plants. Seed cost was $0.71 per thousand PLS, based on a local retail price of $276 kg^{-1} (Jason Tronbak, personal communication, Millborn Seeds) and seed weight of 386,000 seeds kg^{-1}. Potting soil cost was $10.30 per thousand plants. Total cost for producing plants for transplanting was $200.21 per thousand plants. Based on actual labor use, transplanting in the field required 8.89 h of labor per thousand plants, or $124.50 per thousand plants. Based on field records, it was estimated that, in the year after establishment, 198 h ha^{-1} was used to remove hybrid cattail by hand. For comparison, we also estimated costs to establish a cordgrass wetland by drilling seed (7.5 kg PLS ha^{-1}) rather than transplanting.

Machinery costs for spraying, seeding, and harvesting were estimated using University of Minnesota machinery cost data (Lazarus 2013). These costs included ownership and operating costs for farm equipment, including operator labor. Annual maintenance costs included 7.4 h labor and $0.99 herbicide ha^{-1}. Since costs for establishment occur before any income is generated, costs and income were all as present values relative to the establishment year using a discount rate of 4 %. Cumulative net present value was then annualized assuming a 10-year life and a 20-year life to provide annual net income estimates. Land rent that could have been earned in crop production was used as a comparison to the annual net income from grass production using the 2013 county average dryland cropland rate of $472 ha^{-1} (NASS 2013). The payback period for a grass stand to recover establishment costs was indicated by the first year that cumulative net present value was≥0. The payback period for a grass stand to exceed the opportunity cost of crop rent was indicated by the first year cumulative net present value exceeded the cumulative net present value from cropland.

Results

Precipitation

Precipitation in 2008, 2009, and 2011 was slightly below normal (Table 1). The establishment year of the gradient experiment, 2010, received above-normal annual and growing season precipitation (Table 1; Fig. 2). The summer of the third year of the gradient experiment, 2012, was the driest on record, although annual precipitation totals were only slightly below normal due to a large rainfall event (150 mm) in early

Table 1 Precipitation (mm) at the Madison, SD weather stations, approximately 25 km from the research site (NOAA 2013)

Year	Annual	Apr-Sept	June-Sept
2008	615	395	276
2009	604	416	305
2010	912	801	692
2011	607	501	313
2012	634	490	164[b]
2013	[a]	376	200
30-year mean	655	495	343

[a] Not available at the time of writing

[b] Lowest since records began in 1981

May. The dry autumn of 2012 coupled with average precipitation in spring 2013 resulted in a very brief period of inundation by shallow water restricted to the center of the gradient experiment wetland. The wetlands of the transplant density experiment did not have standing water in 2013.

Establishment Along Gradient

For the Prairie Farm population, planting technique interacted with relative elevation to influence establishment success. Transplanting plugs was more successful than drilling seed regardless of the elevation; however, this difference was greater near the wetland bottom than on the slopes (Table 2). Success on the wetland bottom was less than on the slopes regardless of planting method. Like Prairie Farm, drilled Red River was more successful on higher slopes than on the wetland bottom. Success of both populations and planting techniques increased from 2011 to 2012, because established plants expanded vegetatively by rhizomes into unoccupied plots.

Vigor Components Along Gradient

In general, plant vigor at low elevations was similar in 2011 and 2012, but was reduced in 2013 (Fig. 3). At high elevations, plant vigor was greatest in 2011. Peak vigor values occurred at lower elevations in 2012 and 2013 than 2011 (Fig. 4). Differences between drilled populations were greatest in 2012, when Prairie Farm vigor was greater than Red River. Plant height was correlated with all measured variables, including biomass ($\rho=0.47$; $p<0.01$). Inflorescence density varied much more than plant height or maximum inflorescence height (Table S1). All three measurements were affected by elevation x year interactions (Tables S2 and S3). Plant height was also affected by a planting x year interaction and a population x year interaction. Maximum inflorescence height also differed by population. Inflorescence density was affected by a population x year interaction.

Density of Prairie Farm inflorescences was greatest in 2012 and lowest in 2013 at the lowest elevations (<0.44 m), but at 0.45 to 0.74 m was greatest in 2011 (Table 3; Fig. S1). In drilled treatments, the number of Red River inflorescences declined every year, whereas Prairie Farm did not change from 2011 to 2012 before declining sharply in 2013 (Table 4). Inflorescence density of Red River was greater than Prairie Farm in 2011 but Prairie Farm was greater than Red River in 2012 (Table 4).

Mean maximum inflorescence height was greater for drilled Prairie Farm than Red River (2.0 vs. 1.5 m; Table 4). There was also an interaction effect of year x position, with height at the lowest position greater in 2012 and 2013 than

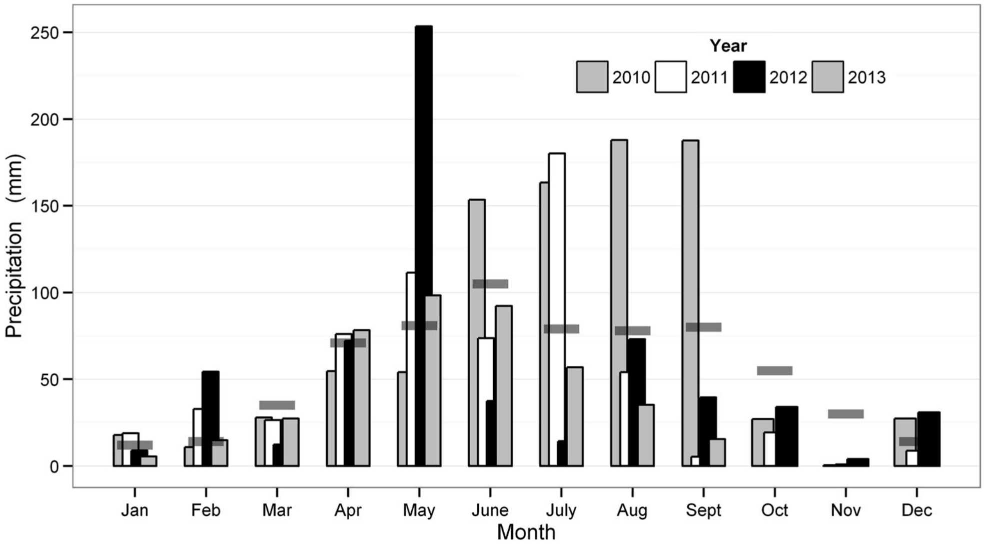

Fig. 2 Thirty-year (1981 to 2010) mean monthly precipitation (horizontal lines) and monthly precipitation (vertical bars) from January 2010 to September 2013 at Madison, SD (NOAA 2013)

Table 2 Percentage success of two different planting techniques for two populations of prairie cordgrass, as affected by relative elevation. Success was defined as at least one tiller being present within the sampling quadrat. Planting occurred in 2010

Population	Planting technique	Relative elevation	Year		
			2011	2012	2013
Prairie Farm	Plug	0 to 0.1 m	65	94	100
Prairie Farm	Drill		0	0	31
Red River	Drill		10	11	15
Prairie Farm	Plug	> 0.1 m	86	96	90
Prairie Farm	Drill		67	74	78
Red River	Drill		57	75	66

2011, but height at higher elevations (0.45 to 0.74 m) greater in 2011 than 2012 (Table 3).

Plant height was greater for drilled Prairie Farm than Red River in all years (Table 4). Plant height was greatest at mid to upper elevations in 2011 but shifted to the lowest elevations in 2012 and 2013.

Biomass Along Gradient

Biomass did not differ between populations or planting techniques in 2013. Biomass was greatest at the middle elevations (0.16 to 0.40 m; Table 5). Within the same wetland, 16 samples were harvested at ground level along the northern edge of the wetland in 2011. Mean biomass of these samples was 14.7 Mg ha^{-1}, with a standard deviation of 5.5 Mg ha^{-1}. These samples were not included in the experimental design.

Transplant Density Experiment

Plug survival at the end of the first growing season was 91 %. Biomass differed between the two planting densities in 2009, the year after planting, but did not differ from 2010 to 2013 (Table 6). Mean yield from 2010 to 2013 was 12.1 Mg ha^{-1}, harvested at ground level.

Economic Analysis

Cordgrass biomass yield was 8.3 Mg ha^{-1} harvested by field-scale equipment to a 12-cm stubble height in the eastern wetland (0.5-ha) at the experimental site in 2012 (Zilverberg et al. 2014). The harvest occurred *after* cordgrass had been combined for seed and some biomass consequently removed. Harvest with field-scale equipment was 60 % of total above ground biomass (Zilverberg et al. 2014). Using this harvest fraction with measured annual biomass production (Table 6), estimated hay production ranged from 5.4 Mg ha^{-1} in 2013 to 8.9 Mg ha^{-1} in 2011, with an average of 7.3 Mg ha^{-1} from 2010 to 2013. Farm-gate prices received for grass hay harvested at the Prairie Farm from 2010 to 2013 ranged from \$55 Mg^{-1} in 2011 to \$110 Mg^{-1} in 2012, with an average of \$81 Mg^{-1}. Costs for establishing

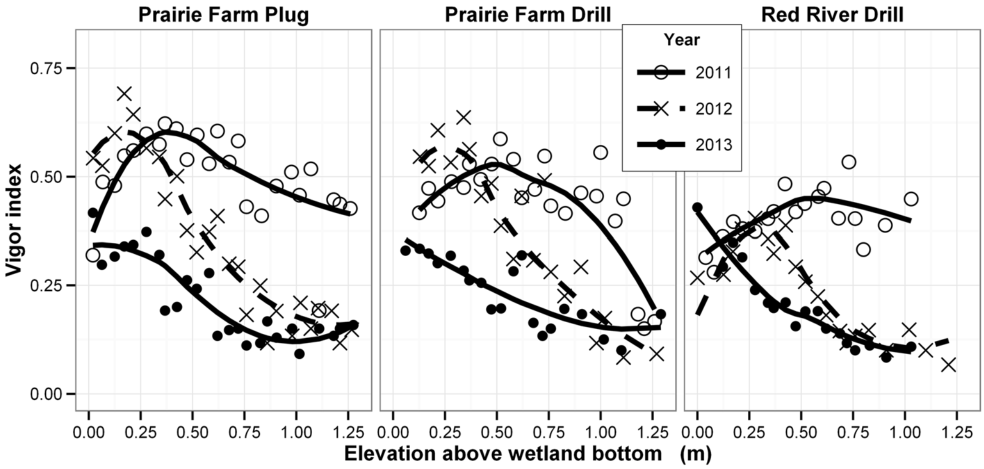

Fig. 3 Vigor index of two populations of prairie cordgrass along an elevation gradient, measured in 2011 (solid line with open circles), 2012 (dashed line with exes), and 2013 (solid line with filled circles). The Prairie Farm population was transplanted from greenhouse plugs or drilled. Samples without a plant were removed from the dataset before analysis. Lines were drawn using the second degree local polynomial technique. Before plotting points, values were averaged across transects and elevation ranges of 0.05 m to improve clarity of graphs

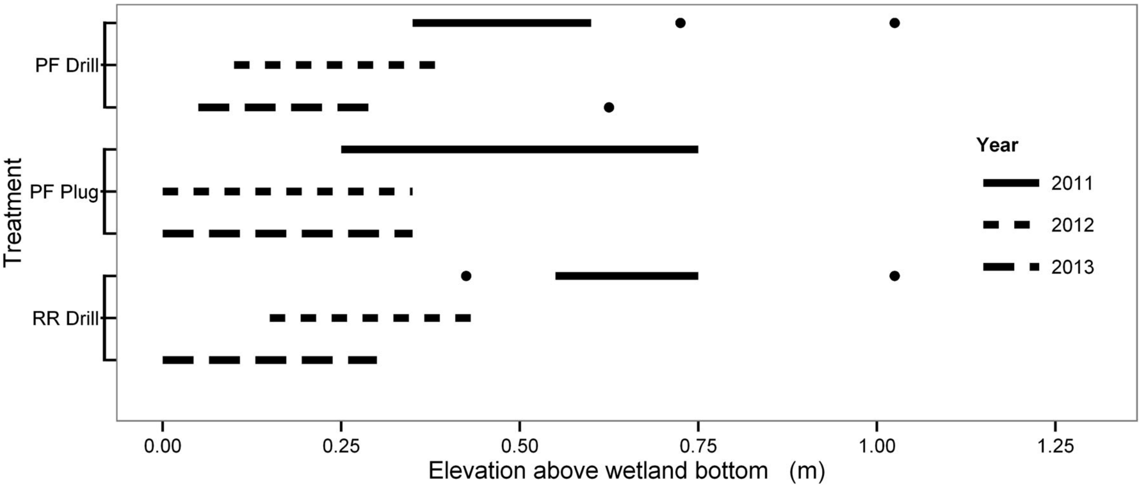

Fig. 4 Range of maximum vigor for each combination of population (PF=Prairie Farm; RR=Red River) x planting technique (Drill or Plug), measured in 2011 (solid line), 2012 (short dashed line), and 2013 (long dashed line). Range of maximum vigor was defined as the upper quartile of vigor values, excluding outliers. Outliers are graphically indicated by filled circles

cordgrass were estimated at $4,040 for the 0.9-m spacing, $1,476 for the 1.5-m spacing, and $2,153 ha^{-1} for direct seeding, excluding land rent.

Using the 2010–2013 average hay yield and price, annualized net income was estimated at -$496,−$192, and −$273 ha^{-1} for a 10-year stand life with the 0.9-m spacing, 1.5-m spacing, and direct seeding, respectively. Annualized net income was -$134, $48, and $0 ha^{-1} for a 20-year stand life with the 0.9 m, 1.5 m, and direct seeding, respectively. Establishment costs were not recovered over a 20 year period for the 0.9-m spacing. The payback periods for the 1.5-m spacing and direct seeding were 17 and 20 years, respectively. Recovering the opportunity cost of cropland rent was not achieved over a 20 year period for any establishment method.

Table 3 Mean values of measured plant characteristics, as affected by population, year, planting technique, and relative elevation along a prairie wetland-upland gradient. With a column, values followed by the same lowercase letter are not different (*p*>0.05). Within a row, values followed by the same uppercase letter are not different (*p*>0.05)

Dependent variable	Population	Planting technique	Year	Relative elevation			
				< 0.15 m	0.15 to 0.44 m	0.45 to 0.74 m	0.75 to 1.38 m
Plant height	Prairie farm & Red river	Drilled	2011	1.0 aZ	1.1 aZY	1.1 aY	1.1 aY
			2012	1.1 aX	1.2 bY	1.0 bX	0.7 bZ
			2013	1.3 bX	1.2 bX	1.0 bY	0.7 bZ
Plant height	Prairie farm	Drilled & plugged	2011	1.1 aY	1.3 aZ	1.3 aZ	1.2 aZ
			2012	1.4 bX	1.4 bX	1.1 bY	0.8 bZ
			2013	1.3 bX	1.3 aX	1.1 bY	0.8 bZ
Maximum inflorescence height	Prairie farm & Red river	Drilled	2011	1.5 aY	1.7 aZ	2.0 aZ	1.9[a]
			2012	1.9 bY	1.9 aY	1.6 bZ	1.2[a]
			2013	2.0 bY	1.8 aZ	1.7 abZ	1.8[a]
Inflorescence density	Prairie farm & Red river	Drilled	2011	8.0 aY	10.2 aY	10.3 aY	4.0 aZ
			2012	8.5 aY	10.8 aY	3.3 bZ	0.7 bZ
			2013	1.2 bZ	1.2 bZ	0.2 bZ	0.0 bZ
Inflorescence density	Prairie farm	Drilled & plugged	2011	9.0 aY	12.1 aY	10.8 aY	4.1 aZ
			2012	16.1 bY	16.2 bY	4.0 bZ	1.0 aZ
			2013	1.0 cZ	0.9 cZ	0.2 cZ	0.0 bZ

[a] Not subjected to statistical analysis due to the small number of observations

Table 4 Mean values of measured plant characteristics, as affected by population, year, planting technique, and relative elevation along a prairie wetland-upland gradient. With a column, values followed by the same lowercase letter are not different ($p>0.05$). Within a row, values followed by the same uppercase letter are not different ($p>0.05$)

Dependent variable	Population	Planting technique	Year		
			2011	2012	2013
Plant height	Prairie farm	Drilled	1.2 aZ	1.2 aZ	1.1 aZ
		Plugged	1.3 aY	1.2 aZ	1.1 aZ
Plant height	Prairie farm	Drilled	1.2 aZ	1.2 aZ	1.1 aZ
	Red river		0.9 bY	0.8 bZ	0.9 bY
Inflorescence density	Prairie farm	Drilled	7.0 aY	7.9 aY	0.4 aZ
	Red river		9.9 bX	3.7 bY	0.9 aZ
			Population		
			Prairie Farm	Red River	
Maximum inflorescence height		Drilled	2.0 Y	1.5 Z	

Discussion

Gradient analysis revealed a zone of maximum prairie cordgrass vigor that shifted downslope to the center of the wetland beginning in 2012, the driest summer on record (Fig. 4). In 2012, the basin recharged with rainwater early in the spring (326 mm precipitation from April-May) but dried out because little moisture was received from June to September (164 mm). Thus, plants were flooded for less time in the dry summer and probably extended roots deeper to reach groundwater. This was most detrimental to plants in the upper portions of the basin and the upland surrounding the wetland, where vigor decreased more rapidly with increasing elevation than in 2011, when the wetland received normal precipitation (Fig. 3). However, the shallow water in 2012 was beneficial for those plants in the basin center, which had presumably been stressed by extended inundation in 2011. Effects of the 2012 drought extended into 2013, when the wetland held much less water despite receiving average precipitation in the spring (Fig. 2).

Zones of maximum production for the two populations overlapped. There was no difference in biomass yield of the two populations ($p=0.58$). Mean yield was greatest (6.0 Mg ha^{-1}) from 0.16 to 0.39 m relative elevation, which corresponded to a maximum water depth of 0.11 to 0.34 m. The most-suited areas for cordgrass production are likely shallow temporary wetlands and seasonal wetlands with short hydroperiods. By using this information to strategically place cordgrass in appropriate wetland environments within production agriculture fields, field-scale biodiversity, and perhaps biomass yield, could be increased.

The two planting techniques resulted in similar vigor and biomass production except in the wetland center, where drilling was ineffective at establishing plants. Within this region from 0 to 0.1 m elevation from the wetland bottom, the equivalent of 0.4 to 0.5 m maximum water depth, standing water in the center of the wetland either prevented germination or killed small seedlings. In contrast, starting plants in the greenhouse before transplanting to the field was effective along the entire elevational gradient. This technique used less seed than drilling at 7.5 kg PLS ha^{-1}, but was more costly at the 0.9-m spacing because it required greenhouse access and more labor. However, for seed prices greater than \$185 kg^{-1}, transplanting at the 1.5-m spacing was less costly than direct

Table 5 Biomass production (Mg ha^{-1}) by two populations of prairie cordgrass planted using two techniques at different elevations above the floor of a wetland basin in 2013. Samples were cut at ground level. Within a row, values followed by the same lowercase letter are not different ($p>0.05$). Values are means of four blocks and two planting techniques (first row) or four blocks and two populations (second row). N=84

Population	Planting technique	Relative elevation						
		< 0.08 m	0.08 to 0.16 m	0.17 to 0.22 m	0.23 to 0.32 m	0.33 to 0.40 m	0.41 to 0.80 m	0.81 to 1.13 m
Prairie Farm	Drill/Plug	1.50 a	4.49 b	6.13 b	5.91 b	6.39 b	1.35 a	0.18 a
Prairie farm/Red river	Drill	0.00 a	3.06 b	5.04 c	5.89 c	6.69 c	1.56 ab	0.04 a

Table 6 Biomass (Mg ha^{-1}) of wetlands planted to prairie cordgrass at 0.9- or 1.5-m spacing in 2008. Within a row, treatments followed by the same lowercase letter were not different ($p>0.05$). N=165

Year	Plant spacing, m	
	0.9	1.5
2009	3.8 a	2.0 b
2010	10.7 a	11.0 a
2011	16.0 a	13.8 a
2012	14.2 a	13.3 a
2013	9.9 a	8.2 a

seeding. Therefore, an optimum establishment strategy would be to transplant into the wetland bottom (maximum water depth > 0.4 m) and drill the higher reaches if seed can be obtained for less than $185 kg^{-1}. Transplanting would be the optimum establishment strategy over the entire wetland area at higher seed costs. In northeastern Kansas, overall survival of transplanted cordgrass plugs was 90 % after 3 years, but decreased to 73 % for small plugs at low elevations (Fraser and Kindscher 2005). Our results after 1 year were similar. Fraser and Kindscher (2001) found that cordgrass plugs tripled in area from 0.51 to 1.57 m^2 over 3 years and that fastest growth occurred at shallow maximum water depth (0.11 to 0.20 m). Boe and Lee (2007) noted that plots with an inter-row spacing of 90 cm and intra-row spacing of 35 cm formed dense sods by the third production year. Although we did not measure basal area, our results indicated that established plants spread into unoccupied space (Table 2).

We observed the Red River population to have a more tussock-like growth form, compared to Prairie Farm, which spread rapidly and obscured the location of the original rows planted. Prairie Farm's natural leaf height and inflorescence height were both greater than Red River, but the populations did not differ in biomass. The height difference might impact benefits to wildlife because if left unharvested over winter, the taller Prairie Farm population might continue to provide wildlife cover after Red River was buried by deep snow. Population interacted with year to impact inflorescence density but had no effect on biomass; both biomass and inflorescence density were sensitive to the effect of elevation.

The decline in inflorescence density from 2012 to 2013 could have been caused in part by drought. However, it has also been observed that cordgrass inflorescence density typically peaks in the second year (unpublished data) and seed production declines dramatically by the 5th year, presumably because stands become sodbound (Jensen 2013). For commercial seed production, plants are usually grown in wide rows (2 to 5 m) and cultivated to promote seed production. A challenge for commercial seed production is that insects that feed in the seedheads and on belowground growing points destroy ovules and reduce seedhead density, especially in stands at least 3 years old (Boe et al. 2009, 2013). Burning and/or N fertilization can partially offset yield declines after the second year (unpublished data).

The planting density experiment found that biomass differed between planting densities for only 1 year after establishment. At that point, stands were still immature and biomass yields were probably too low to justify harvesting. Therefore, it is unlikely that the additional time and materials required to plant at 0.9-m spacing rather than 1.5-m spacing were justified.

Cordgrass biomass yield data in the literature are scant, but our yields at the highest elevations, upslope of a temporary wetland, were similar to yields from another experiment on gravelly upland soils (1.4 Mg ha^{-1}; Boe et al. 2009). Preliminary yield data collected in the gradient experiment in 2011 (data not shown) suggested that yields declined from 2011 to 2012, presumably due to the dry summer through winter in 2012. Within our zone of optimal production and after a severe drought, yield in the gradient experiment was lower than other experiments on good soils (6.4 and 11.7 Mg ha^{-1}; Boe and Lee 2007 and Boe et al. 2009) and in natural stands (9 Mg ha^{-1}; Albertson and Weaver 1944). Yields obtained in this experiment within the optimum production zone were similar to switchgrass yields at other sites on the experimental farm, collected using similar techniques (unpublished data). Yield from the transplant density experiment peaked at 14.9 Mg ha^{-1} (in 2011) and were similar to yields taken from the northern border of the wetland in the gradient experiment (14.7 Mg ha^{-1}) in 2011. Both were similar to the plot yield of 14.6 Mg ha^{-1} reported by Boe et al. (2009).

Based on the economic value of the biomass, recovering the opportunity cost of cropland rent was not achieved over a 20 year period for any establishment method. However, this was on land that would be subject to frequent crop failures due to wet conditions, and thus may not be generating sufficient revenue from conventional crops to cover cropland rent. In addition, our analysis included the use of a large amount of labor to remove hybrid cattail—an expensive activity that was conducted on the experimental farm but would probably not be undertaken in a typical production field. Had this cost not been incurred, establishment costs were estimated to be recovered in 17, 7, and 9 years for the 0.9-m spacing, 1.5-m spacing, and direct seeding, respectively. Establishment costs were higher for direct seeding than for transplanting at the 1.5-m spacing due to the larger amount of seed used with direct seeding and the high cost of seed.

Harvesting cordgrass seed offers a highly variable but potentially profitable supplement to biomass harvesting. Across the farm, seed yield was ~5 to 15 kg PLS ha^{-1} from 2010 to 2013. These yields were lower than the "average" range of 34 to 84 kg ha^{-1} reported by the NRCS (2012), presumably because the areas were not intensively managed for seed production. That is to say, they were never fertilized and only rarely burned. In addition, many were narrow strips that were difficult to harvest mechanically. However, in the eastern experimental wetland, which was well suited for cordgrass growth, we achieved a yield of 60 kg PLS ha^{-1} in the year (2012) after the wetland was burned, and sold the seed to a retailer for \$150 kg^{-1} PLS. While similar seed harvests would likely occur infrequently, revenue from one such harvest occurring within 10 year of planting would recover all establishment costs and annualized net returns would exceed cropland rent. The farm-gate price received for prairie cordgrass seed has ranged from \$143 to 165 kg^{-1} over the period 2010–2013. Currently, most cordgrass seed is used for conservation plantings, but the market could expand if cordgrass is used as a biofuel crop. Even at a low annual yield of 5 kg PLS ha^{-1}, annual gross revenue would increase by \$750 ha^{-1} at current market prices, establishment costs for the 1.5-m spacing would be recovered within 7 years, and opportunity cost of land rent would be recovered in 14 years.

The value of ecosystem services provided by restored wetlands may not have market prices and are not easily estimated. Restored wetlands can improve floristic quality, native plant species diversity, and nesting and foraging sites for wildlife, as well as provide floodwater attenuation and sequester carbon (Euliss et al. 2006; Gleason et al. 2008). Although biomass removal might impact some of these services, delaying biomass harvest until after a killing frost would reduce many negative consequences. For instance, an autumn harvest would not interfere with nesting requirements for wildlife during spring and summer.

As grain farms in the Prairie Pothole Region grow in size, so does the machinery used for farming. As the scale of farming equipment increases, so does the inconvenience of driving around a restored wetland within a field whose uplands are planted to grain. Therefore, despite the potential economic and ecological benefits provided by restored wetlands, we anticipate restoring wetlands for commercial harvest is most likely to occur on smaller farms (<260 ha) with numerous shallow wetlands.

Conclusions

Both populations of prairie cordgrass evaluated in this study produced excellent stands within their zone of adaptation in shallow wetlands; however, the Prairie Farm population is a more robust plant than Red River and when not hayed may provide better winter cover for wildlife.

Prairie cordgrass plugs established well throughout shallow wetlands. Increasing plug spacing from 0.9-m to 1.5-m produced similar biomass yields by the third year and reduced establishment costs. Drilling seed was less labor intensive than placing plugs, but can fail to establish cordgrass in the deeper parts of wetlands. An optimum establishment strategy would be to use plugs in the wetland center and drill where maximum water depth exceeds 0.4 m.

Marketing of prairie cordgrass hay and seed currently yields sufficient income to offset the costs of its planting and management in previously farmed prairie wetlands. Establishment of prairie cordgrass is most likely to be adopted on smaller farms with numerous shallow wetlands.

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