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Establishment and early productivity of perennial biomass alley cropping systems in Minnesota, USA

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Abstract In May 2010, alley cropping systems consisting of switchgrass (*Panicum virgatum* L.), prairie cordgrass (*Spartina pectinata* Bosc ex Link), an alfalfa (*Medicago sativa* L.) and intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth and Dewey) mixture, and a native tallgrass-forb-legume polyculture, planted between multi-row strips of poplar hybrid 'NM6' (*Populus maximowiczii x P. nigra*) and willow cultivar 'Fish Creek' (*Salix purpurea*) were established at Empire and Granada, Minnesota, USA. Crop establishment and productivity were characterized for each species over two growing seasons and at two distances from the tree-crop interface. Prairie cordgrass and the native polyculture were among the most productive herbaceous crops at both sites, averaging between 7.1 and 11.9 Mg DM ha^{-1}, and have shown no evidence of competition for resources along the tree-crop interface thus far. Basal area (BA) was similar at Empire for NM6 (1,744 mm^2 tree^{-1}) and Fish Creek (1,609 mm^2 tree^{-1}), but was greater for NM6 (1,045 mm^2 tree^{-1}) than Fish Creek (770 mm^2 tree^{-1}) at Granada. Despite this, stand basal area (SBA) was greater for Fish Creek at both sites due to greater planting density. Across species, BA and SBA were greater for trees along the alley than those in center rows at Empire, whereas no difference was observed at Granada. Results suggest that alley cropping provides suitable conditions for establishment of short-rotation woody and certain herbaceous biomass crops, and that some of these crops may be well suited to the alley cropping environment. However, continued research is needed to evaluate crop persistence and productivity as crops and trees mature and the potential for interspecies competition increases.

Keywords Alley cropping · Biomass · Short rotation woody crops · Native grasses · Establishment

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Introduction

Marginal agricultural lands in the US Midwest have the potential to produce 5.5 billion gallons of renewable fuels each year using perennial biomass crops (Gelfand et al. 2013). This amounts to 25 % of next generation fuels required under the former mandate of the Energy Independence and Security Act, or just over 6 % of projected best-case liquid transportation fuel needs by 2050 (EISA 2007). Furthermore, it's estimated that this is possible with no initial carbon debt or the indirect land-use costs typically associated with biofuels derived from food crops (Gelfand et al. 2013). Agroforestry has been proposed as an ideal system for producing cellulosic biomass crops on marginal lands due to the potential to satisfy a broad suite of social, economic, and environmental objectives (Holzmueller and Jose 2012; Bardhan and Jose 2012). Targeting perennial biomass crop-based agroforestry systems to marginal lands could help to maximize landscape productivity, improve economic returns for landowners, and reduce risk through a more diversified approach to crop production (Thelemann et al. 2010). Furthermore, such an approach would add value to the farming enterprise by providing ecosystem services such as improvement of air and water quality, conservation of biodiversity, soil enrichment, and carbon sequestration (Jose 2009).

Alley cropping, the planting of crops between rows of woody perennials, is an agroforestry practice that shows particular promise in temperate regions (Thevathasan and Gordon 2004). Research has shown that alley cropping can have beneficial effects on crop growth due to reduced heat and wind stress, reduced evaporative loss, lower soil surface temperatures, and increased soil moisture due to moderate shading by trees (Jose et al. 2004; Clinch et al. 2009; Quinkenstein et al. 2009). In addition, above- and below-ground tree litter inputs can have beneficial impacts on soil chemical, physical, and biological properties in alley systems (Cardinael et al 2012; Thevathasan and Gordon 2004; Jose 2009). However, improper species selection and tree-crop spatial arrangement can result in competition for resources between trees and crops. This, in turn, can result in poor crop establishment, reduced overall productivity, and ultimately crop failure (Jose et al. 2004; Garrett et al. 2009).

Little information exists regarding the performance of biomass crops in alley cropping systems, but a few early studies have shown promising results. Cardinael et al. (2012) and Clinch et al. (2009) found that short rotation willow (*Salix* spp.), a potential cellulosic biomass crop, yielded better in mixed hardwood alley cropping systems than in monoculture in southern Ontario. There have also been studies in the southern US demonstrating favorable early productivity, soil C accumulation, and economic potential of loblolly pine (*Pinus taeda* L.)—switchgrass (*Panicum virgatum* L.) alley cropping (Blazier et al. 2012; Susaeta et al. 2012). However, we currently have little understanding of optimal crop species combinations, planting arrangements, rotation lengths, and long-term production potential of woody and herbaceous biomass crops in alley cropping systems in the North Central Region of the United States (Bardhan and Jose 2012). Therefore, the objective of this study was to assess the suitability of selected woody and perennial herbaceous biomass crops for alley cropping systems by evaluating crop establishment and early productivity at two Minnesota sites.

Materials and methods

Study site and experimental design

The study was established in May and June 2010 at two privately owned farm sites in Minnesota. Sites were located on a floodplain near Granada, MN (43°45′28″N; 94°20′48″W), and on a stream terrace near Empire, MN (44°39′59″ N; 93°06′39″W), hereafter referred to as "Granada" and "Empire", respectively. Soils at Granada are very deep, poorly to somewhat poorly drained, formed in alluvium, and consist of the Coland (Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls) soil series (Table 1). Soils at Empire are very deep, somewhat poorly drained, formed in loamy alluvium overlying sand and gravel outwash and are of the Cylinder (Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aquic Hapludolls) soil series. Slopes at both sites range between 0 and 5 %.

Granada was in a long-term corn (*Zea mays* L.)—soybean (*Glycine max* [L.] Merr.) rotation and Empire was in continuous corn prior to establishment of the experiment. Repeated applications of municipal biosolids by the landowner at Empire prior to establishment of the experiment resulted in greater organic matter, and soil P, K, and fall residual nitrate-N levels at this site compared to Granada. Flooding at Granada in 2010 resulted in one replicate being fully submerged for 21 days and partially submerged for about 36 days, while the other two replicates were submerged for about 15 days. One replicate at Empire was submerged for about 7 days during this period. Average annual temperature at Granada is 7.4 °C and at Empire 6.4 °C. Average annual rainfall at Granada is 79 cm and at Empire 88 cm.

Table 1 Selected soil characteristics at two Minnesota sites prior to establishment of the alley cropping experiment

Site	Soil type	Bray P (ppm)	NH_4OAc-K (ppm)	pH	Organic matter (%)	C/N ratio	Fall residual NO_3^- (ppm)[a]
Empire	Loam	964	236	5.5	5.2	8.98	25.4
Granada	Silty clay loam	36	114	6.4	3.6	11.96	11.4

Samples were collected to 15.24 cm (6 in.) depth and are the average of three replicates

[a] Fall residual nitrate samples were collected in fall 2010 following the first growing season

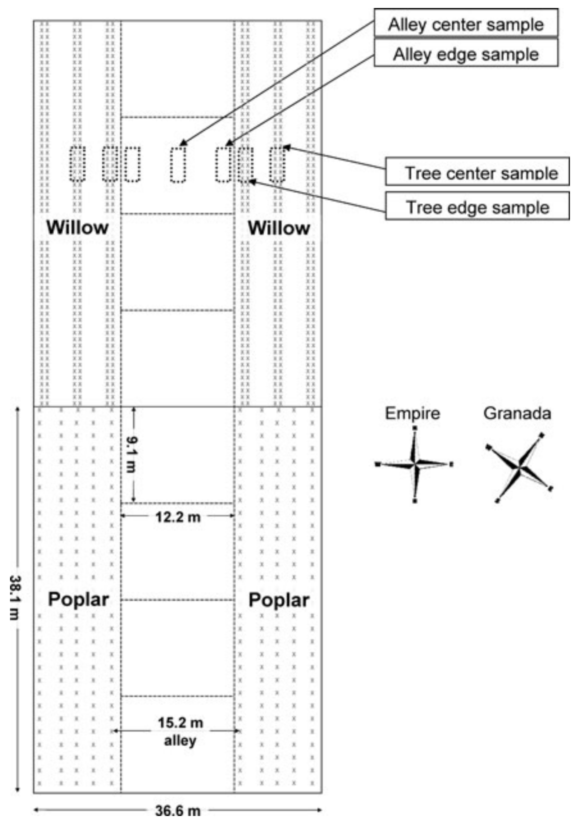

Fig. 1 Example layout and sampling locations to assess potential differences in woody stand characteristics and herbaceous dry matter production relative to distance from the tree–crop interface for one replicate of the split plot alley cropping system. Treatment names are provided for illustrative purposes.

The experimental design was a randomized complete block in a split plot arrangement. Three replicates were established at each site, with short-rotation woody crops (SRWC) randomly assigned to 38.1 m by 36.6 m whole plots and herbaceous crops randomly assigned to 12.2 m by 9.1 m sub-plots within each whole plot. Multi-row hedgerows were planted to create high-density strips of SRWC (Gruenewald et al. 2007), which increases feedstock density and harvest efficiency relative to single rows. Hedgerows of SRWC were separated by a 15.2 m alley (Thevathasan and Gordon 2004; Reynolds et al. 2007), a spacing wide enough to allow agricultural machinery to work across the field. Four sub-plots were nested within the alley between SRWC, leaving a 1.5 m unsown buffer to minimize root competition between trees and crops during establishment (Fig. 1). Alley orientation differed between sites due to landowner preferences and site features. At Empire, alley orientation was North–South, while at Granada it was approximately Northwest–Southeast (replicates 1 and 2) and East–West (replicate 3). The allocation of land area within each replicate was approximately 40 % trees, 48 % herbaceous crops, and 12 % unsown buffer between the two.

System configuration

Alley cropping systems consisted of four herbaceous biomass crops and two SRWC. Herbaceous crops were switchgrass (*Panicum virgatum* L.), prairie cordgrass (*Spartina pectinata* Bosc ex Link), a mixture of Pioneer Brand '54V48' alfalfa (*Medicago sativa* L.) and 'Rush' intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth and Dewey), and an eleven species native tallgrass-forb-legume polyculture (switchgrass, prairie cordgrass, alfalfa-intermediate wheatgrass, and native polyculture, respectively). Woody crops were poplar hybrid 'NM6' (*Populus maximowiczii x P. nigra*) and willow cultivar 'Fish Creek' (*Salix purpurea*).

Switchgrass and native polyculture seed were grown or collected in Minnesota and were purchased from a commercial seed company (Feder Prairie Seed Company, Blue Earth, MN). The native polyculture contained two warm season (C_4) grasses, one cool season (C_3) grass, four forbs, and four legumes, representing 68.8, 10.7, 16.7, and 3.8 % of the mixture by seed count, respectively. Prairie cordgrass rhizomes planted at Granada were collected from a nearby wild population, while those at Empire were a 'Red River' cultivar obtained from a previous study in St. Paul, MN. Alfalfa and intermediate wheatgrass seed were obtained from a commercial seed company (Albert Lea Seed House, Albert Lea, MN), and the initial mixture was 64 % alfalfa and 36 % intermediate wheatgrass by seed count.

Both sites were cultivated and the soil packed with a roller/packer to provide a firm seed bed before planting. Herbaceous crops, with the exception of prairie cordgrass, were planted by manually broadcasting seed across the plot area. Prairie cordgrass was established from live rhizomes hand planted at 0.3 m within and between rows. Alfalfa and intermediate wheatgrass were seeded at rates recommended for conservation plantings, 5.7 kg pure live seed (PLS) ha^{-1} and 9.0 kg PLS ha^{-1}, respectively (Ogle et al. 2003; USDA-NRCS 2006). The native polyculture was seeded at 18.2 kg PLS ha^{-1} based on guidelines outlined by Jacobsen (2006) for native grassland establishment. Native legume seeds were scarified using a mechanical compressed air/sandpaper scarifier and were inoculated with appropriate rhizhobia before planting using a modification of the recommendations of Tlusty et al. (2004), as directed by B. Tlusty (personal communication). Switchgrass was seeded at 16.8 kg PLS ha^{-1}, approximately 25 % greater than the rate recommended by the USDA-NRCS (2006). Germination and emergence is generally lower with broadcast versus drilled switchgrass seed (Mitchell and Vogel 2012), so the seeding rate was increased accordingly. Plots that were broadcast seeded were packed with a roller/packer immediately following seeding to ensure seed to soil contact. Herbaceous plots were mowed twice during 2010 to control weeds; once in mid-July and once in late July or early August, except for prairie cordgrass plots, which were mowed only in mid-July and were hand weeded once thereafter. No efforts were made to control weeds in herbaceous plots during the second growing season in 2011.

Woody crops were established at each site in May 2010 by first cultivating and packing the soil with a roller/packer to provide a firm seed bed. Unrooted 25 cm willow and poplar stem cuttings were obtained from commercial nurseries (Double A Willow Inc., Fredonia, NY, and Lodholz North Star Acres, Inc., Tomahawk, WI, respectively) and were planted to a depth of approximately 20 cm, leaving one or two buds above ground level. Willows were established following guidelines in the Willow Biomass Producer's Handbook (Abrahamson et al. 2002) in a high-density twin row coppice system with 75 cm between rows, 60 cm between plants within a row, and 150 cm between twin rows, resulting in a density of 14,332 willows ha^{-1} Three twin rows of willows created a 5.3 m hedgerow on either side of the herbaceous alley. Willows were coppiced during dormancy following the first growing season to encourage the development of multiple stems, rapid shoot growth, and canopy closure (Abrahamson et al. 2002; Volk 2002). Poplars were established at 1.2 m within and between rows in a density of 6,670 plants ha^{-1} (DeBell at al. 1996; DeBell et al. 1997; Benomar et al. 2012), with five rows of poplar creating a 4.9 m hedgerow on each side of the alley. In contrast to willow, poplar were not coppiced since research has shown that first year coppicing results in no yield benefit in high-density poplar plantations (Hervé and Ceulmans 1996; Volk 2002). Willow plants were sprayed with 1.1 kg ha^{-1} a.i. oxyfluorfen [2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluromethyl)benzene] and 2.2 kg ha^{-1} a.i simazine (6-chloro-*N*,*N*′-diethyl-1,3,5-triazine-2,4-diamine) shortly after planting for pre-emergent weed control and were cultivated in June 2011 for post emergence weed control. Manual weed removal was performed as needed in poplar plots during 2010. In mid-June 2010, about 3 weeks after planting, any poplar and willow trees with no visible growth were replaced with fresh un-rooted cuttings to ensure adequate stocking.

Data collection and statistical analysis

Establishment of SRWC was assessed by determining tree survival in each plot 3 and 12 months after planting. All willow and poplar trees in each plot were counted in August 2010 and May 2011 at each site to determine survival. Productivity was assessed by collecting poplar and willow plant heights, diameters, and stem counts following plant senescence in 2011, and calculating individual tree basal area (BA, mm^2 $tree^{-1}$) and stand basal area (SBA, m^2 ha^{-1}). Data were collected for trees along the tree-crop interface (representing a tree–crop interaction) and in the center of the plot (representing little or no tree–crop interaction) for each SRWC x herbaceous crop combination, $n = 6$ for willow and $n = 8$ for poplar in each sample location. Hereafter, these will be referred to as the "edge" and "center" row positions, respectively. Stem diameters were measured at a height of 30 cm for willow and at 140 cm for poplar. The height of the tallest living stem in each plant was measured to the nearest centimeter.

Establishment of herbaceous crops, with the exception of prairie cordgrass, was assessed by counting the number of plants, by species, in three randomly selected 0.3-m^2 quadrats in each sub-plot 45 days after planting. These data were used to determine botanical composition and to calculate an establishment index, which is the ratio of the number of seeds emerged in the field relative to the number of germinable or emerging seeds planted (Mitchell and Vogel 2012). Prairie cordgrass establishment was determined by recording the survival of nine plants in each of three randomly selected 1-m^2 quadrats in each sub-plot in November 2010 and calculating an establishment index with these data.

Herbaceous biomass yield was measured in fall of 2010 and 2011 following a killing frost (0 °C) or plant senescence. Samples of the herbage were harvested in each sub-plot within the alley in the fall to determine dry matter production. In 2010, all plant material in three randomly selected 1-m^2 quadrats was harvested to a 10 cm stubble height at each of the two tree–crop interfaces in the alley and three were harvested in the middle of the sub-plot, centered at 7.6 meters from the nearest tree, for each treatment combination. Hereafter, these will be referred to as the alley "edge" and "center" positions, respectively, for herbaceous dry matter yield. In 2011, all plant material in a 2.78 square meter area (0.91 × 3.05 m) was mechanically harvested to a 10 cm stubble height in the center and both edge positions in each sub-plot. A visual estimate of ground area occupied by crop and weed species in each sampling area was also conducted at this time to determine stand vigor. In both years, samples were weighed in field following harvest to obtain fresh weights. Randomly collected sub-samples of at least 1,000 g were dried in a 60 °C oven to a constant weight and weighed again to obtain dry matter (DM) yield and moisture content. Weed biomass was estimated by manually separating weeds from the crop biomass in dried sub-samples and weighing weed biomass separately.

Fixed effects analysis of variance (ANOVA) was used to test for main effects and interactions between whole plot and sub-plot treatments as well as effects of site and distance from the tree–crop interface (edge vs center positions), except for BA analysis, for which a linear mixed effects model was used treating the whole plot error term as random. For the mixed effects model, variance components of random effects were estimated by restricted maximum likelihood (Patterson and Thompson 1971), and approximate likelihood ratio tests using nested null and alternative hypothesis models were performed to verify the significance of components by maximum likelihood (Pinheiro and Bates 2000). Alley orientation was confounded with site and, at Granada, replicate and flood frequency. As a result, the effects of flooding and alley orientation are indistinguishable from the effects of replicates and were therefore not considered separately in the analysis. For all analyses, where significant ($P \leq 0.05$) effects were found, Tukey's honestly significant difference (HSD) test for multiple comparisons was used to determine differences between means. Where interactions, main effects, and distance from the tree-crop interface were not significant, Student's *t* test was used to test the significance of site.

Results and discussion

Short rotation woody crops

Willow survival was similar at both sites in August 2010, about 96 %, while poplar survival was 98 % at Empire and 95 % at Granada. Willow survival was similar in August 2010 and May 2011 at both sites, as was poplar survival at Empire. At Granada, poplar survival declined from 95 % in August 2010 to about 92 % in May 2011. This was likely due to mortality from extensive flooding. In the most frequently flooded replicate at Granada, trees were submerged for about 36 days and poplar survival declined from 94 % in August 2010 to 83 % in May 2011. Willow survival in this replicate did not change. The two other replicates at Granada were submerged for about 15 days, which did not reduce poplar or willow survival. First year survival of poplar and willow trees at both sites exceeded the 80 % survival threshold noted by Bergkvist et al. (1996) for productive stands of SRWC.

In fall of 2011, poplar at Granada averaged 1.5 stems tree^{-1} and were similar between edge and center row trees. At Empire, there were 2.4 stems tree^{-1} in edge row poplar, but only 2.0 stems tree^{-1} in center rows. *Populus* are primary successional, shade intolerant species (Baker 1949; Demerrit Jr. 1990) that show reduced shoot growth in shade (Farmer 1963; DeByle et al. 1985) and increased numbers of shoots as light availability increases (Ek et al. 1983). There was no effect of row position on tree height, though poplar height was greater at Empire than at Granada, at 556 and 514 cm, respectively. The number of stems per willow was 21.8 at Empire and 13.0 at Granada, with stem numbers being similar for edge and center row trees. Average willow height was 337 cm at Empire and 296 cm at Granada, and no differences were observed between edge and center row trees. No edge effects were observed for willow, despite *Salix* spp. also being shade intolerant, primary successional species (Argus 1986).

Basal area (BA) was 1,676 mm^2 tree^{-1} at Empire and 907 mm^2 tree^{-1} at Granada, when averaged across row position and species, and was greater at Empire than Granada for both row positions and SRWC (Fig. 2). When averaged across row position, poplar trees at Granada had greater BA than willow trees, despite greater mortality due to flooding. There

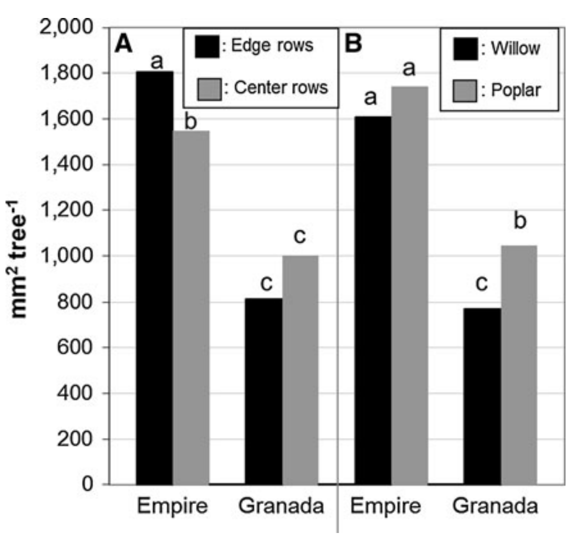

Fig. 2 Basal area (BA) per tree for alley cropped short rotation woody crops at two Minnesota sites in the year following establishment: **A** in edge and center rows and **B** by species. Within each panel, bars with the same letter are not significantly different based on Tukey's HSD (0.05)

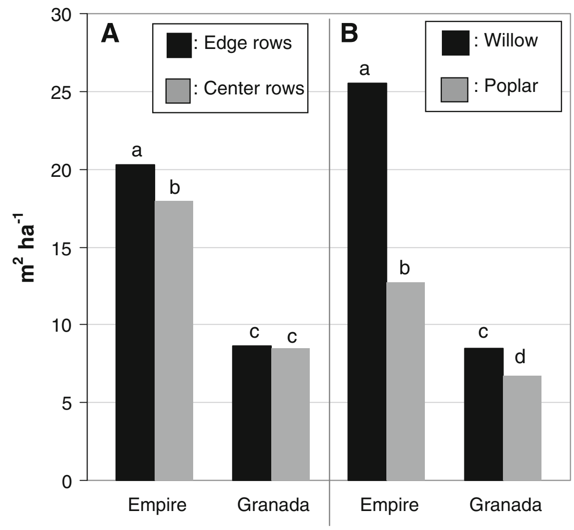

Fig. 3 Stand basal area (SBA) per hectare for alley cropped short rotation woody crops at two Minnesota sites in the year following establishment: **A** in edge and center rows and **B** by species. Within each panel, bars with the same letter are not significantly different based on Tukey's HSD (0.05)

was no difference in BA between willow and poplar trees at Empire. When averaged across species, BA was greater in edge row than center row trees at Empire, whereas no difference was detected between row positions at Granada. Stand basal area (SBA) ranged from 6.7 to 25.5 m^2 ha^{-1} (Fig. 3) and was greater at Empire than Granada for both row positions and SRWC. Despite similar or lower BA than poplar, willow SBA was greater at both sites due to greater planting density. No difference in SBA was found between edge and center row trees at Granada, whereas SBA was greater in edge rows than center rows at Empire.

Increased growth of trees in edge rows at Empire and the lack thereof at Granada suggest that alley orientation is influencing tree growth patterns in the alley system. At Empire, the tree rows were planted in a North–South orientation, whereas Northwest–Southeast (replicates 1 and 2) and West–East orientations (replicate 3) were used to accommodate site features at Granada. No information exists regarding optimal row orientation for SRWC in alley cropping systems, which are typically grown in densely spaced block plantations where effects of row orientation are unlikely. However, in orchard settings, North–South rows have been found to favor increased fruit growth and yield relative to East–West rows (Christensen

1979). Conversely, East–West oriented alleys have been found to favor alley crop rather than tree production, especially in northern temperate latitudes (Mutsaers 1980; Nygren and Jiménez 1993). In loblolly pine plantations in the Southeast United States, no distinction in tree height and BA can be made between North–South and East–West row orientations, even when considering a wide range of tree ages, planting densities, and row widths (Amateis et al. 2009). Our findings show that North–South alleys result in an edge effect along the tree–crop interface, whereas no edge effect was observed in other alley orientations. However, trees within the center of the hedgerow of both species had greater SBA at Empire than Granada, suggesting that differences in overall tree productivity between sites extend beyond the effects of alley orientation. Repeated flooding and tree submergence during the establishment year at Granada and higher fertility at Empire must also be taken into consideration when comparing tree productivity between sites. More research is needed to characterize potential differences in light availability between edge and center row positions relative to alley orientation, and to examine how these factors affect productivity of both woody and herbaceous crops in the present study.

Herbaceous alley crops

Establishment index and weed density

Establishment index ranged from 0.18 to 0.93 and did not differ between sites for seeded treatments (Table 2). Alfalfa-intermediate wheatgrass had a higher establishment index than switchgrass and the native polyculture at both sites. Establishment index for the native polyculture ranged from 0.18 to 0.21 in this study, whereas Mangan et al. (2011) found an average of 0.05 for a similar native polyculture that was broadcast seeded at eight Minnesota sites. Establishment indices for switchgrass have been found to range from 0.1 to 0.45 for a variety of cultivars when planted with a seed drill, and are typically lower when broadcast seeded (Mitchell and Vogel 2012). At 0.21 and 0.33, the establishment indices for our broadcast-seeded switchgrass are solidly in this range, though our switchgrass was seeded at higher than recommended rates. For prairie cordgrass, the only crop planted from rhizomes, establishment index was greater at Empire than Granada at 0.92 and 0.82, respectively, with both values in the range reported for other successful vegetatively propagated prairie cordgrass stands (Potter et al. 1995). Despite differences in establishment index, weed density did not differ between treatments or between sites, except for switchgrass, which had greater weed density at Empire than at Granada.

Biomass yield and ground cover

In 2010, fall herbaceous biomass yield ranged from 3.0 to 7.0 Mg DM ha^{-1} and was similar between sites (Fig. 4a). At Granada, yields of alfalfa-intermediate wheatgrass, native polyculture, and switchgrass did not differ but were greater than prairie cordgrass yield, whereas at Empire, dry matter yield was similar among all crops.

Table 2 Planting rate, establishment index, and weed density for four herbaceous alley crops at two Minnesota sites 45 days after seeding

Treatment	Planting rate (PLS m^{-2})	Establishment index[b]		Weed density (seedlings m^{-2})	
		Empire	Granada	Empire	Granada
Switchgrass	1,481	0.21 br	0.33 br	90.4 ar	38.8 as
Alfalfa–wheatgrass	439	0.82 ar	0.90 ar	69.9 ar	30.1 ar
Native polyculture	770	0.18 cr	0.21 br	73.2 ar	72.1 ar
Prairie cordgrass[a]	10.8	0.93 r	0.82 s	NA[c]	NA

Within each column and row, means with the same letter are not significantly different based on Tukey's HSD (0.05). Letters a–c are used to denote differences among treatments, while letters r–s are used to denote differences between sites

[a] Live rhizomes were planted rather than seed, thus comparisons to seeded treatments were not made

[b] Establishment index is calculated as average seedling density/planting rate

[c] *NA* Not applicable; this data was not collected due to the need for manual weed management

In 2011, fall herbaceous biomass yield at Empire averaged 8.2 Mg DM ha^{-1} compared to 4.7 Mg DM ha^{-1} in 2010, whereas yield was similar between years at Granada (average of 5.4 Mg DM ha^{-1}) when averaged across crops. There were differences in herbaceous crop yield between sites by 2011 (Fig. 4b), but crop yield did not differ between poplar and willow alleys, or as a result of distance from the tree-crop interface. At Granada, alfalfa-intermediate wheatgrass yielded less than all other treatments. At both sites, yield was lower than that reported by Sleugh et al. (2000), who found that an alfalfa-intermediate wheatgrass mixture yielded 12.7 Mg DM ha^{-1} in the year following establishment in central Iowa. However, this was based on four harvests throughout the growing season, in contrast to the single-cut fall harvest used in our study.

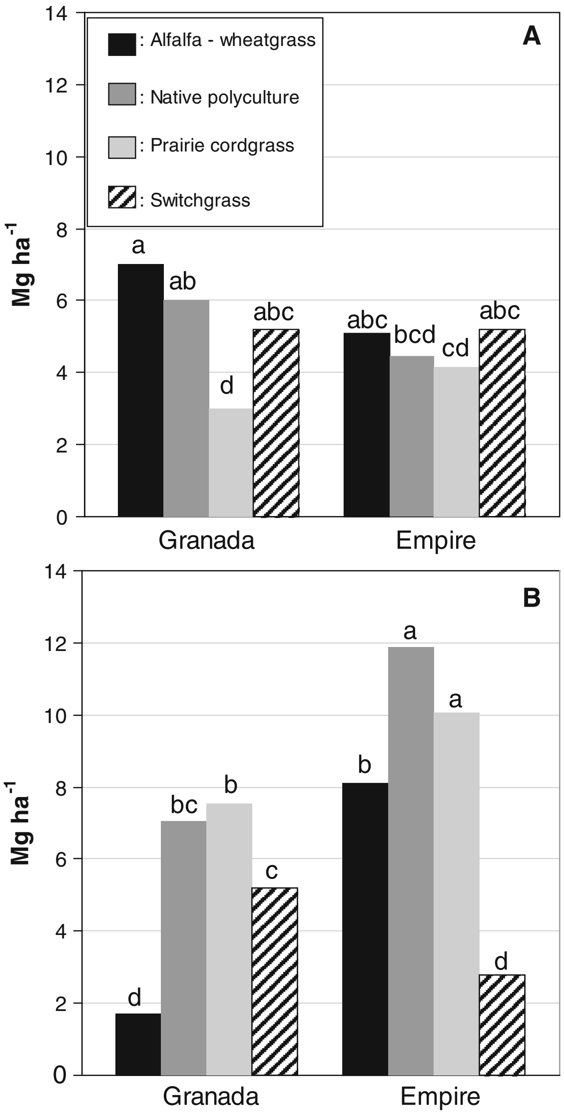

Fig. 4 Dry matter yields for four herbaceous biomass alley crops at two sites in Minnesota in **A** 2010, the establishment year and **B** 2011, the year following establishment. Within each year, bars with the same letter are not significantly different based on Tukey's HSD (0.05)

Switchgrass yield at Granada was 5.2 Mg DM ha^{-1}, whereas at Empire it was 2.8 Mg DM ha^{-1} and was likely reduced due to high weed density. These yields are less than the 8.5 Mg DM ha^{-1} reported by Mangan et al. (2011) for locally (Minnesota) sourced switchgrass on heavy soils with low weed pressure, but greater than the 0.2 Mg DM ha^{-1} they reported under extreme weed pressure.

Prairie cordgrass was among the more productive crops at each site, yielding 10.1 and 7.6 Mg DM ha^{-1} at Empire and Granada, respectively. These results compare favorably to second year yields of 6.0 Mg DM ha^{-1} reported by Boe and Lee (2007) and are on track for mature stand (4–10 year) yields of 12.6 Mg DM ha^{-1} reported Boe et al. (2009). Similarly, native polyculture yields in this study were 11.9 and 7.1 Mg DM ha^{-1} at Empire and Granada, respectively, and compared favorably to other reports. For example, Mangan et al. (2011) found second year yields of a similar native polyculture ranged between 1.5 and 6.9 Mg DM ha^{-1} across eight Minnesota sites.

By fall 2011, crop ground cover varied among crops and between sites (Table 3). At Empire, weed cover was low in the native polyculture, and crop cover in this treatment was predominantly Canada wild rye (*Elymus candensis* L.), a C_3 grass. Ground cover in native polyculture plots at Granada was nearly equally distributed between C_3 grasses, C_4 grasses, and forbs. Legumes were scarce in the native polyculture at Empire and alfalfa-intermediate wheatgrass at Granada, while at Granada, legume coverage was approximately 10 % in the native polyculture. Weeds were the predominant ground cover in alfalfa-intermediate wheatgrass at Granada, likely due to poor crop tolerance of flooding. At Empire weeds were the predominant ground cover in switchgrass, while at Granada, switchgrass was predominant. Prairie cordgrass cover was approximately 90 % at both sites, though crop ground cover was greatest in the native polyculture at 95 % or greater at both sites.

Table 3 Percent ground cover by functional group for four herbaceous alley crops at two Minnesota sites following the second growing season in October 2011

Site	Treatment	Functional group				Weeds	Total crop cover
		C_3 grasses	C_4 grasses	Forbs	Legumes		
		% cover					
Empire	Switchgrass	NA[a]	40 (7)	NA	NA	58 (7)	40
	Alfalfa–wheatgrass	94 (1)	NA	NA	3 (1)	3 (1)	97
	Native polyculture	87 (3)	0	9 (1)	2 (1)	2 (1)	98
	Prairie cordgrass	NA	92 (1)	NA	NA	8 (1)	92
Granada	Switchgrass	NA	86 (4)	NA	NA	14 (4)	86
	Alfalfa–wheatgrass	27 (9)	NA	NA	0	70 (9)	27
	Native polyculture	29 (1)	28 (1)	28 (1)	10 (1)	5 (1)	95
	Prairie cordgrass	NA	88 (2)	NA	NA	12 (2)	88

Means are presented followed by standard errors in parentheses

[a] *NA* Not applicable; no species of this functional group were seeded into the treatment

The native polyculture yielded well in both years, despite low establishment indices and relatively high weed density 45 days after seeding. This contrasts with the expectation of slow establishment for native grassland plantings (van Ruijven and Berendse 2005). However, Canada wild rye (*Elymus Canadensis* L.), an early successional, cool-season species, provided the majority of ground cover at Empire (87 %), and a large portion of cover at Granada (29 %) by fall 2011, even though it comprised only 11 % of the seed mixture.

Relatively high soil nutrient levels, especially at Empire, may explain the predominance of Canada wild rye and may also explain why we saw rapid establishment and high yields of our polyculture relative to other published accounts. High soil nutrient levels can increase the presence of cool season species in polycultures, causing declines in other functional groups over time (Rehm et al. 1976; Pan et al. 2010), resulting in dominance by only a few highly competitive species (Pywell et al. 2003). Without a cool-season species such as Canada wild rye in our polyculture, we likely would have had more competition from weeds and slower establishment for this treatment. This was the case for switchgrass at Empire, which had good initial establishment but competed poorly with cool season annual weeds in both years. In contrast, prairie cordgrass had low weed cover and yielded well despite being a warm season species. However, prairie cordgrass generally emerges earlier in the season than switchgrass (Guo et al. 2012), which may account for differences in ground cover and yield between these species at Empire.

Conclusions

During the first two years following establishment, herbaceous alley crops showed no evidence of competition for resources along the tree-crop interface, suggesting that alley cropping with SRWC provides a suitable environment for establishment. Yields of herbaceous crops were generally on par with those reported for experimental monoculture production systems in the region, except for switchgrass at Empire and alfalfa-intermediate wheatgrass at Granada, which were poorly adapted to conditions at those sites.

Tree survival was similar at both sites at greater than 90 %, but NM6 poplar and Fish Creek willow growth were superior at Empire compared to Granada. Frequent flooding at Granada during the first year as well as higher nutrient availability at Empire likely contributed to these differences between sites. Proximity to the alley had beneficial effects for tree growth in North–South alleys at Empire, whereas no effect was seen at Granada, where alley orientation was approximately Northwest – Southeast and West-East. Despite these clear differences in edge effects, the overall effect of alley orientation on tree productivity is still unclear. Finally, despite similar or lower BA than NM6 poplar, Fish Creek willow SBA was greater at both sites due to greater planting density.

Overall, the results of this study suggest that alley cropping provides suitable conditions for establishment of SRWC and certain herbaceous biomass crops, depending on site characteristics, and that many of these crops may be well suited to the alley cropping environment. However, as horizontal and vertical growth of trees continues, the potential for resource competition will increase. More research is needed to evaluate how the alley cropping environment affects long-term persistence and productivity of SRWC and herbaceous biomass crops.

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