

Biophysical interactions in perennial biomass alley cropping systems

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Abstract Understanding the nature and degree of competition between trees and co-planted crops in agroforestry systems can inform management decisions, future species selection, and system design. We measured variation in herbaceous biomass yield, photosynthetically active radiation (PAR), soil water potential, and residual soil NO_3 in alley cropping systems consisting of prairie cordgrass (*Spartina pectinata*) or an 11-species native grass-forb-legume polyculture planted between rows of shrub willow (*Salix purpurea* L. ‘Fish Creek’) at two Minnesota sites. At Empire, biomass yield increased with distance from the tree row for both alley crops, as did PAR and NO_3 availability. At Granada, no spatial pattern in crop yield was evident, despite reduced PAR and NO_3 availability adjacent to tree rows. At both

sites, patterns in soil water potential suggested that trees competed with crops for soil water within 2.4 m of tree rows, but had a facilitative effect on crop water use at 4.8 m. Alleys had differing cardinal orientations at the two sites, and light availability was lower in a north–south alley (Empire) than in west–east and northwest–southeast orientations (Granada). At Empire, mixed effects analysis indicated that competition for light and soil water were responsible for reductions in crop yield. For every 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ increase in PAR, model estimated herbaceous crop yield increased by 623 kg DM ha^{-1} . For every 20 kPa increase in average daily water potential, crop yield increased by 1038 kg DM ha^{-1} . The relative impact of competition on biomass yield was similar for both crops, though prairie cordgrass had higher average yields at Empire. Similar alley systems should avoid north–south alley orientations to minimize competition for light.

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Introduction

Polyculture plantings of multiple species are sometimes recommended to increase land productivity over

monoculture plantings (Malézieux et al. 2009). Agroforestry, the integration of trees and shrubs with agronomic crops or pasture, is one commonly promoted polyculture approach that can add social, economic, and ecological value to agricultural landscapes. However, competition between trees and co-planted crops can reduce productivity in agroforestry systems to a point where mixed-culture is not economically justified. Competition occurs when coexistent plants reduce the availability of one or more growth resources to the point where growth or survival of either is negatively impacted (García-Barrios and Ong 2004; Harper 2010). Management interventions such as fertilization, irrigation, and tree pruning can alleviate competition if they are informed by an understanding of the nature, degree, and timing of competition.

Agroforestry systems composed of short-rotation woody crops (SRWC) and herbaceous perennials have shown potential for producing biomass and bioenergy (Gamble et al. 2014; Ehret et al. 2015; Lamerre et al. 2015). In these systems, fast growing SRWC such as hybrid poplar (*Populus* spp.) and shrub willow (*Salix* spp.) are planted in high-density strips, with perennial herbaceous biomass crops in inter-row alleys. These arrangements result in a novel system where the tree component is harvested on short rotations of 4 or 5 years, creating a spatially and temporally dynamic growing environment for both woody and herbaceous crops.

Our previous work with perennial biomass alley cropping has shown no evidence of competition between trees and crops up to 3 years after establishment (Gamble et al. 2016). However, by the fourth year, we found that in hybrid poplar and shrub willow alleys at one Minnesota site, yield of four herbaceous perennial biomass crops was reduced along the tree-crop interface relative to the center of the alley (Gamble et al. 2016). At two other Minnesota sites, no competitive effects were observed on alley crop yield. Alley orientation differs among the three sites, which is undoubtedly responsible for some of the difference in competitive effects. However, the exact mechanisms responsible for crop yield reductions at the Empire site remain unclear.

The degree of competition, and ultimately crop yield, in multi-species systems is dependent on the spatial and temporal partitioning of light, water, and nutrients among species (Howard et al. 1996; Jose

et al. 2000b). A comprehensive understanding of the partitioning of resources is critical for identifying the nature and degree of competition between a given tree-crop pairing. Greater understanding, in turn, improves our ability to design systems to reduce competitive effects and increase yield while maintaining the positive benefits of mixed-culture.

Light, water, and nutrient dynamics are not well understood in perennial biomass alley cropping systems. This has led us to further investigate (1) the resources that define productivity in these systems, and (2) the role that alley orientation plays in resource distribution. Here, we aim to better understand how interactions with short rotation shrub willow ‘Fish Creek’ (*Salix purpurea* L.) influence biomass yield of two herbaceous perennial biomass crops, prairie cordgrass (*Spartina pectinata* Bosc ex Link) and an 11-species native polyculture, in an alley cropping configuration at two environments in Minnesota. Our objectives were to (1) evaluate spatiotemporal variation in PAR, soil matric potential (water potential, hereafter), and soil NO₃-N in these systems, (2) to determine how differing alley orientations between sites impacted PAR, and (3) to determine how the availability of these resources impacted herbaceous biomass alley crop yields.

Materials and methods

Study site and experimental design

We collected data in 2013 from an ongoing study that was established in May and June 2010 at two 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; Table 1). 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. 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. Average annual temperature at Granada is 7.4 °C and at Empire 6.4 °C. Growing season (April–October) precipitation at Granada was 518 mm in 2013, which was 21%

Table 1 Selected site and soil characteristics at Empire and Granada, MN

Characteristic	Empire	Granada
Latitude, longitude	44.7178, – 93.0975	43.7575, – 94.3465
Landform	Stream terrace, outwash plain	Floodplain
Soil classification	Cylinder loam (fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic aquic hapludolls)	Coland loam (fine-loamy, mixed, superactive, mesic cumulic endoaquolls)
Depth to water table	Approx. 45 cm	Approx. 15–45 cm
Soil organic matter (g kg ⁻¹) [†]	58	33
Soil pH [†]	5.6	6.3
Soil NO ₃ -N (mg kg ⁻¹) [†]	42.3	6.8
Soil Bray P (mg kg ⁻¹) [†]	761	25
Soil NH ₄ OAc-K (mg kg ⁻¹) [†]	229	86
Previous management	Continuous corn with municipal biosolids	Corn–soybean rotation
Alley orientation (rep 1, 2, 3)	0°, 0°, 0°	90°, 100°, 135°

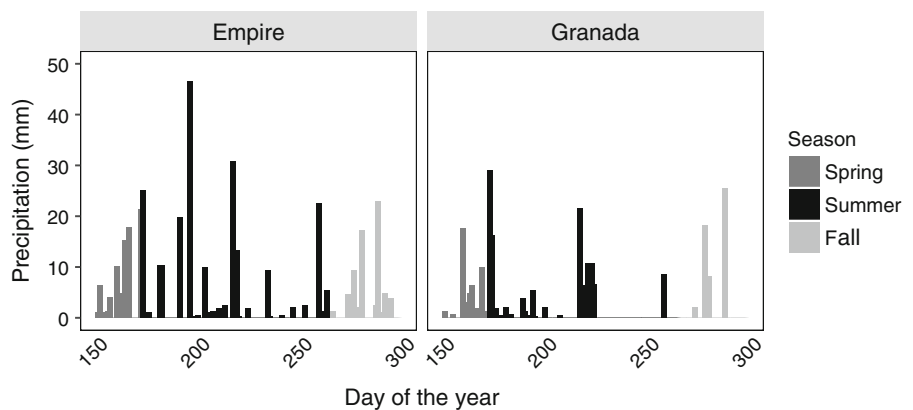
[†]Soil samples collected in November 2012

below the 30-year climatological mean over this period. At Empire, 2013 growing season precipitation was 582 mm, which was 16% below the 30-year mean. At both sites, the majority of this deficit occurred between July and September, following above average precipitation in April and May (Fig. 1). The prevailing wind direction during the growing season is south-southeast at Granada and south at Empire, with average wind speeds during the

2013 growing season of 4.2 and 2.9, ms⁻¹, respectively.

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. However, no

Fig. 1 Seasonal precipitation at Empire (left) and Granada (right) Minnesota by day of the year from 31 May to 25 October 2013



additional fertilizer was applied throughout the study period at either site.

The experimental design was a randomized complete block in a split-plot arrangement. Three replicates were established at each site. Two SRWC were randomly assigned to 38.1 by 36.6 m whole plots and four herbaceous crops were randomly assigned to 12.2 m by 9.1 m subplots within each whole plot. Woody crops were established in multi-row strips, with a 15.2 m alleyway (Fig. 2). Alley orientation differed between sites as a result of 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). Further detail about sites and experimental layout can be found in Gamble et al. (2016).

For the present study, a subset of plots was chosen for instrumentation and detailed data collection. Alley cropping systems were prairie cordgrass (*Spartina pectinata* Bosc ex Link), and an eleven species native tallgrass-forb-legume polyculture nested between rows of willow cultivar ‘Fish Creek’ (*Salix purpurea*). At establishment, 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. By the 2013 growing season, the mixture was predominated by forbs and cool season grasses at Empire. The composition at Granada was much more

balanced, with a small native legume population and roughly equal proportions of C_4 grasses, C_3 grasses, and forbs.

Field and laboratory methods

Relative PAR and crop LAI

A Decagon AccuPar LP-80 Ceptometer (Decagon Devices Inc., Pullman, WA) was used to measure incident photosynthetically active radiation (PAR, 400–700 nm) and leaf area index (LAI) in the alleys. Diurnal transmission of incident PAR was measured above the herbaceous crop canopy at five locations in a transect across the alley every 2 h from 09:00 to 17:00 h on 18 and 19 July, 2013. Ten random samples were measured and the average recorded in the center of the alley, and at 2.4 and 4.8 m from tree rows on either side of the alley under cloudless conditions. Incident PAR outside the alley system was also measured one meter above the ground before and after measuring for each transect. Data collected outside the alley system displayed a concave shape when plotted against time, and were thus fit to a nonlinear quadratic function (data not shown). This function was used to estimate incident PAR outside the alley system for each minute throughout the sampling period. Relative PAR was calculated as (I_c/I_o) where I_c is the incident PAR at the top of the

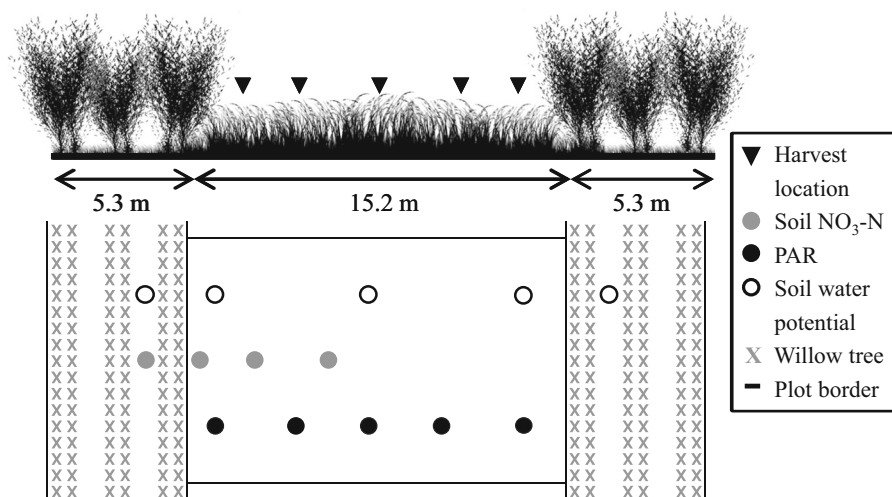


Fig. 2 Cross-sectional view of the willow-grassland alley cropping system with crop harvest locations (top), and aerial plot layout of the willow-grassland alley cropping system with soil NO₃-N, PAR, and soil water potential sampling locations (bottom)

herbaceous canopy within the alley, and I_0 is the model estimated PAR in open conditions.

LAI, defined as the projected leaf area per unit ground area was measured for herbaceous crops during late-July 2013. LAI measurements were taken in the center of the alley and at both tree-crop interfaces (2.4 m from tree rows). A measurement consisted of a simultaneous reference measurement above the canopy and the average of ten below-canopy readings. All measurements were taken at ground level either early in the morning or late in the afternoon to allow for diffuse light conditions (Tharakan and Volk 2005).

Soil water potential

Soil water potential was monitored continuously throughout the 2013 growing season using MPS-2 dielectric water potential sensors paired with EM50 data loggers (Decagon Devices, Pullman, WA). Sensors were buried 15 cm below the soil surface, and data loggers were programmed to record hourly from 31 May to 25 October 2013. In each instrumented plot, five sensors were installed in a transect across the alley. One sensor was installed between willow twin rows on each side of the alley, one sensor was installed in the center of the herbaceous plot (7.6 m from the nearest tree row), and two sensors were placed at intermediate positions within the plot, 2.4 m from tree rows on either side of the alley. Hourly matrix potential readings were averaged by day and grouped by season for analysis (spring, 25 May to 21 June; summer, 22 June to 22 September; and fall, 23 September to 25 October).

Soil nitrate-N

Soil cores were collected in November 2013 in four depth increments (0–15, 15–30, 30–60, and 60–90 cm), except at Empire, where a gravel layer prevented collection of samples in the 60–90 cm increment. Cores were collected with a hydraulic probe truck equipped with a high relief bit to minimize soil compaction (40.8 mm ID probe tip). In each sub-plot, cores were collected at four distances from the tree row: 0 m (immediately adjacent to trees), 1, 3.5, and 6 m from the tree row. At each sampling location, three cores were collected and composited by depth increment to increase sample volume. The samples

were sent to a commercial laboratory (Agvise Laboratories, Benson, MN, USA) where they were air-dried, ground using a mechanical grinder and ball mill, and analyzed for $\text{NO}_3\text{-N}$.

Herbaceous biomass yield

Biomass yield of herbaceous alley crops was measured in Oct 2013 following a killing frost (0 °C). Herbaceous biomass was harvested from a 2.78 m² area (0.91 × 3.05 m) with a flail-type forage harvester to a 10 cm stubble height in five strips within each alley sub-plot. Strips were located in the alley center (7.6 m from the nearest tree row), at both edge positions (2.4 m from the nearest tree row), and two intermediate positions (4.8 m from tree rows). Herbaceous samples were weighed following harvest to obtain fresh weights and 1000 g sub-samples were dried in a 60 °C to a constant weight to calculate dry matter yield. Weed biomass was manually separated from crop biomass in dried sub-samples to obtain weed free biomass yield estimates.

Tree height

Following senescence in the fall of 2013, the height of the tallest living stem in each plant was measured to the nearest centimeter for a subset of trees ($n = 24$) in each whole plot, with an equal number of trees measured on each side of the alley.

Statistical analysis

To evaluate spatial variation in biomass yields, we expressed sampling distance as the ratio of distance from the tree row to tree height (D/H, hereafter) to account for the potential combined influence of these factors. Initial data exploration included plotting biomass yield against D/H. After determining the best-fit model for the effect of D/H on biomass yield, we added the categorical variable “crop type” and an interaction term with D/H to determine if the effect of D/H was the same for both crops. We compared the best-fit model with the crop type covariate to one without using the maximum likelihood ratio test (Johnson and Omland 2004).

To assess the spatial or temporal availability of growth resources within alley systems, response variables included relative PAR, water potential, and

soil $\text{NO}_3\text{-N}$. Mixed effects ANOVA was used to test the effects of crop (native polyculture vs. prairie cordgrass), distance from the tree row, and soil depth on fall residual soil nitrate. For water potential, mixed effects ANOVA was used to test for main effects of crop, and distance from the tree-crop interface within Fish Creek willow whole plots for each season. For relative PAR, mixed effects ANOVA was used to test for effects of sampling time of day and distance from the tree-crop interface. Each response was analyzed by site, except soil water potential, which was analyzed by site and season. For all analyses, effects of replicates were considered random. To account for spatial autocorrelation occurring as a result of sampling at multiple, systematic locations within the same subplot, we allowed the effect of distance from the tree-crop interface to vary by subplot by nesting distance within subplot as a random effect.

A linear mixed effects model was constructed to evaluate differences in relative PAR between alley orientations. For this analysis, alley orientation was considered a continuous, fixed effect. Alley orientation ranged from 0° to 135° , where 0° is north–south and 90° is west–east. Effects of tree height, tree LAI, time of day, distance, side of the alley, and D/H were considered random. A model with only random effects was used to determine the variance associated with each. The proportion of variance was calculated as the ratio of the variation associated with each random effect to the total variation. This approach allows for variation in the dependent variable to be assessed across levels of the random effects. The results can therefore be generalized to a greater hypothetical population of levels (West et al. 2014), in this case, alley orientations.

To assess the effects of PAR, water potential, and soil $\text{NO}_3\text{-N}$ on herbaceous biomass yield, we used mixed-effects ANOVA treating the effects of PAR, water potential, and soil NO_3 as fixed, and the effects of replicate, crop, and subplot as random. All two- and three-way interactions between explanatory variables were tested. The average of fall and summer mean daily water potential values was used for this analysis as it was assumed to best represent the water stress experienced by herbaceous crops. Since soil NO_3 and biomass yield were assessed at different distances, we assumed that the 6 m NO_3 sample corresponded to the 7.6 m biomass sample, while the mean of the 1 m and 3.5 m NO_3 samples corresponded to the 2.4 m

biomass sample. We tested for multicollinearity among predictors using the “vif” function in “usdm” package with program R (Naimi 2013) and found that none of the predictors showed substantial multicollinearity ($\text{VIF} < 5$, Rogerson 2010).

Linear mixed effects models and mixed effects ANOVA were fit using the “lme4” package with program R (Pinheiro et al. 2013; R Core Team 2016). The probability for rejection of the null hypothesis was set at $\alpha = 0.10$. Where significant effects were found, Tukey’s honestly significant difference (HSD) test for multiple comparisons was used to compare treatment means.

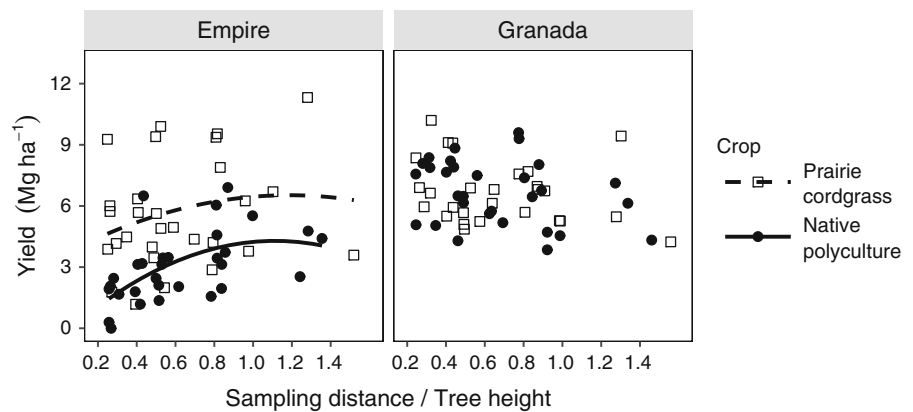
Results

Spatial variation in herbaceous crop productivity and tree height

At Empire, herbaceous biomass yield response to distance from the tree row to tree height (D/H) showed a concave pattern, suggesting that a nonlinear quadratic function should be fit and tested against other models (Fig. 3). We compared the quadratic model to the linear form and also to a model without D/H (intercept-only) using maximum likelihood ratio tests. We then added the categorical variable “crop type” and an interaction term with D/H to determine if the effect of D/H was the same for both crops. A mixed effects model that included terms for D/H (L ratio = 13.21, $P = < 0.001$), a quadratic polynomial effect of D/H (L ratio = 4.75, $P = 0.029$), and for crop (L ratio = 6.19, $P = 0.013$) best predicted herbaceous crop yield (Table 2). Including a term for the interaction between crop type and D/H did not improve model fit. Prairie cordgrass and the native polyculture exhibited similar responses to D/H, with yield increasing from 0.25 to 1.14 D/H, and then declining slightly from 1.15 to 1.52 D/H. However, yield of prairie cordgrass was greater than that of the native polyculture over the range of observed D/H, as indicated by the differing intercepts.

At Granada, no pattern was apparent in the herbaceous biomass yield response to D/H, and including terms for a linear or quadratic polynomial effects of D/H on biomass yield did not improve model fit. A mixed effects model that included a term for the effect of crop best predicted herbaceous crop yield

Fig. 3 2013 biomass yield of prairie cordgrass and native polyculture crops with respect to sampling distance (expressed as distance from the tree row/tree height, D/H) at Empire and Granada, MN. Data from both sides of the alley are pooled



(L ratio = 10.55, P = 0.005), though mean yield was similar for prairie cordgrass (7.1 Mg ha^{-1}) and the native polyculture (6.5 Mg ha^{-1}).

Leaf area index showed similar patterns to distance from the tree row as biomass yield. At Empire, LAI was similar for prairie cordgrass (5.5 ± 0.8) and the native polyculture (4.7 ± 0.5), but varied by distance from the tree row (Table 3). When averaged across crops, LAI was greater in the center of the alley (5.5 ± 0.6) than adjacent to tree rows (average of 3.8 ± 0.3). At Granada, herbaceous crop LAI averaged 3.2 ± 0.2 , and was similar for both crops and all distances from the tree row. Average willow height was 577 cm at Empire and 542 cm at Granada by the end of the 2013 growing season.

Soil water potential

In spring, average daily water potential was similar for all crops and distances from the tree row at both sites, averaging -9.6 kPa at Empire and -13.2 kPa at Granada. In summer, average daily water potential

varied by crop and distance from the tree row at both Empire and Granada. At Empire, water potential in prairie cordgrass alleys was highest in the center of the alley (7.6 m; Table 4). In native polyculture alleys, water potential was lower in the center of the alley than at either 2.4 m east or west. Water potential was higher in the eastern than the western willow rows, but both rows had lower water potential than in prairie cordgrass alleys. In contrast, water potential in the center of the native polyculture alley was similar to that of the west willow row.

At Granada, water potential was lower in native polyculture than prairie cordgrass alleys at all distances from the tree row and was lower in willow rows than in either crop alley. In both prairie cordgrass and native polyculture alleys, water potential was lower on the northern edge (2.4 m north) than the southern edge (2.4 m south) of the alley.

In fall, average daily water potential varied by crop and distance from the tree row at both Empire and Granada. Water potential at Empire was similar for all distances from the tree row in prairie cordgrass alleys.

Table 2 Parameter estimates from best fitted mixed effects models for 2013 herbaceous biomass yield at Empire and Granada, MN

Site	Variable	β	SE (β)	t -value	p -value
Empire	Intercept	- 0.2768	1.1353	- 0.244	0.1389
	D/H [†]	7.9601	2.4915	3.195	< 0.001
	D/H ²	- 3.4990	1.5785	- 2.217	0.02929
	Crop: Prairie cordgrass	2.7766	1.0725	2.589	0.01286
Granada	Intercept	6.6777	0.8414	7.936	< 0.001
	Crop: Prairie cordgrass	0.7907	1.1899	0.664	0.521

[†]Distance from tree row/tree height

Table 3 Tests of fixed effects on soil water potential, soil NO₃-N, LAI, and PAR

Response	Effect	Empire			Granada		
		F val.	P (> F)	Sig	F val.	P (> F)	Sig
LAI	Crop (A)	13.36	0.004	**	1.28	0.377	ns
	Distance (B)	8.44	0.003	**	0.12	0.886	ns
	A × B	0.96	0.482	ns	0.17	0.981	ns
Soil NO ₃ -N	Distance (A)	16.29	< 0.001	***	17.85	< 0.001	***
	Depth (B)	59.57	< 0.001	***	32.58	< 0.001	***
	A × B	2.93	0.008	**	3.88	< 0.001	***
Relative PAR	Time of day (A)	9.30	< 0.001	***	3.93	0.004	**
	Distance (B)	31.57	< 0.001	***	111.71	< 0.001	***
	A × B	21.95	< 0.001	***	3.39	< 0.001	***
Spring water potential	Crop (A)	0.65	0.466	ns	2.04	0.227	ns
	Distance (B)	1.06	0.376	ns	1.06	0.376	ns
	A × B	1.65	0.159	ns	1.65	0.159	ns
Summer water potential	Crop (A)	0.23	0.656	ns	1.32	0.314	ns
	Distance (B)	35.52	< 0.001	***	159.33	< 0.001	***
	A × B	69.9	< 0.001	***	43.49	< 0.001	***
Fall water potential	Crop (A)	0.08	0.466	ns	2.09	0.221	ns
	Distance (B)	41.24	< 0.001	***	125.74	< 0.001	***
	A × B	15.09	< 0.001	***	37.63	< 0.001	***

*Significant at 0.1 level of probability

**Significant at 0.01 level of probability

***Significant at 0.001 level of probability

†ns not significant at the 0.1 level of probability

In native polyculture alleys, water potential was lower in the center of the alley than at either 2.4 m west or east. Willow rows had lower water potential than in crop alleys, except in the center (7.6 m) of native polyculture alleys. At Granada, water potential was similar for all distances from the tree row in prairie cordgrass alleys. In native polyculture alleys, water potential was lowest on the northern edge of the alley (2.4 m north). Water potential was lower in willow rows than at any distance in the crop alleys, except for at 2.4 m north in native polyculture alleys.

Relative PAR and alley orientation

At Empire, relative PAR varied by distance from the tree row and time of day. Compared to the center of the alley, relative PAR was reduced along the eastern edge of the alley during the morning and reduced along the western edge of the alley in the afternoon (Fig. 4). The western half of the alley received most of its PAR

during the morning when the eastern half was shaded. This pattern was reversed in the afternoon when the western half was shaded and the eastern half received a greater amount of PAR. During midday, shading was similar between the furthest east and furthest west sampling distances and relative PAR was similar at the central three sampling distances.

At Granada, relative PAR also varied with distance from the tree row and time of day. Compared to the center of the alley, relative PAR was reduced along the southern edge of the alley during the morning hours and declined further throughout the day. The northern half of the alley received relatively consistent levels of PAR throughout the day, while relative PAR declined slightly in the center of the alley from midday to late afternoon.

A linear mixed effects model that included a term for alley orientation better predicted relative PAR across sites than the intercept-only model (Table 5). For every 10° increase in cardinal alley orientation

Table 4 Average daily soil water potential at 15 cm depth in alley cropping systems at two Minnesota sites

Site	Season	System	Distance from tree row (m)				
			0 (S/W tree row) (kPa)	2.4 S/W (kPa)	7.6 (center) (kPa)	2.4 N/E (kPa)	0 (N/E tree row) (kPa)
Empire	Summer	Willow—native polyculture	– 119.54ar [†]	– 60.17br	– 202.60cr	– 91.47dr	– 81.00dr
		Willow—prairie cordgrass	– 148.36ar	– 54.74br	– 25.44cs	– 48.123br	– 146.41ar
	Fall	Willow—native polyculture	– 186.31ar	– 39.82cr	– 109.93br	– 65.71cr	– 81.01br
		Willow—prairie cordgrass	– 181.65ar	– 20.67br	– 19.49bs	– 22.73br	– 213.31ar
Granada	Summer	Willow—native polyculture	– 102.54br	– 44.52er	– 67.68dr	– 88.99cr	– 150.23ar
		Willow—prairie cordgrass	– 136.32ar	– 26.44dr	– 47.29 cr	– 44.30 cr	– 79.94bs
	Fall	Willow—native polyculture	– 140.87bs	– 48.21dr	– 54.58dr	– 112.88cr	– 178.14ar
		Willow—prairie cordgrass	– 215.89ar	– 23.57cr	– 27.78cr	– 25.68cs	– 85.23br

[†]Means followed by the same letter are not different ($P > 0.1$). Letters a–d are used to denote differences within rows, while letter r–s are used to denote differences within sites and seasons (columns)

Table 5 Parameter estimates and variance partitioning from best fitted mixed effects models for 2013 effects of alley orientation on relative PAR at Empire and Granada, Minnesota

Variable–fixed	β	SE (β)	<i>t</i> -value	<i>p</i> -value
Intercept	0.582118	0.1123	5.182	0.00101
Alley orientation	0.001963	0.0007711	2.546	0.01784
Variable–random	Variance	SD	Proportion of variance	<i>p</i> -value
Time of day	0.034	0.188	0.21	< 0.001
Distance from tree (D)	0.043	0.208	0.23	< 0.001
Tree height (H)	0.000	0.0	0.00	1.0
D/H	0.007	0.083	0.09	0.0140
Plot	0.000	0.0	0.00	1.0
Tree LAI	0.033	0.181	0.20	< 0.001
Residual variance	0.058	0.242	0.27	NA

(0°–180°), model estimated relative PAR increased by approximately 2%. This corresponds to 26% greater relative PAR in 135° alleys than 0° alleys. Random effects for sampling time and distance from the tree explained 44% of model variance. Of the remaining variance, 20% was explained by tree LAI, 9% was explained by the ratio of sampling distance to tree

height, and the remaining 27% was residual, within plot variance. Tree height and whole plot accounted for no additional variance in the model.

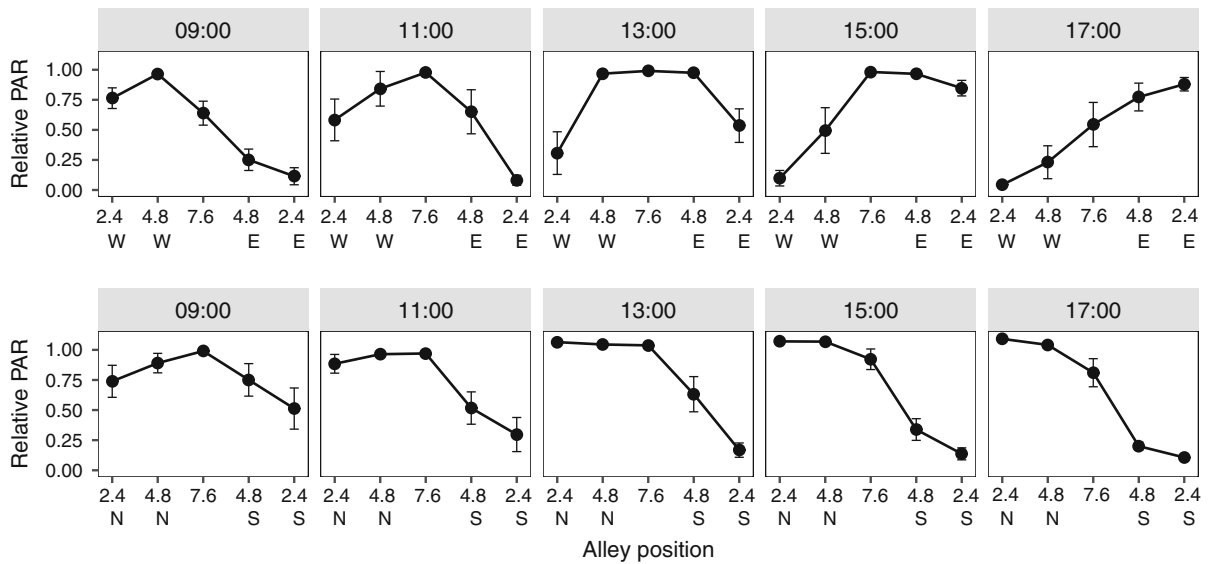


Fig. 4 Diurnal relative PAR in Empire (top panels) and Granada (bottom panels) alley cropping systems by alley position on July 18 and 19, 2013. Alley positions are denoted as distance from the nearest tree row (m) and direction from

alley center (N, S, E, W). Relative PAR was estimated every 2 h between 09:00 and 17:00 h, for five total sampling times. Each panel represents one sampling time. Error bars represent one standard error of the mean

Soil nitrate-N

At both sites, fall residual soil NO₃-N was similar in willow-prairie cordgrass and willow-native polyculture alley systems, so the following analysis is pooled by crop. Fall residual NO₃-N at Empire varied by a soil depth and distance interaction (Fig. 4). At 0–15 and 15–30 cm depths, NO₃-N generally increased with distance from the tree row, whereas at 30–60 cm depth, no effect of distance was observed. Soil NO₃-N decreased with depth, except at 0 m, where it was similar at all depths. Soil NO₃-N at Granada also varied by a soil depth and distance interaction. At 0–15

and 15–30 cm depths, NO₃-N generally increased with distance from the tree row, whereas at 30–60 and 60–90 cm, no effect of distance was observed. Soil NO₃-N was similar for all depths at 0 and 1 m from tree rows (Fig. 5).

Effects of light, water, and nitrate availability on biomass yield

Given the observed yield reductions observed for both herbaceous crops at Empire, linear mixed effects models were constructed to assess the effects of PAR, water potential, and soil NO₃-N on herbaceous

Fig. 5 Fall 2013 residual soil nitrate-N with distance from the tree row and soil depth in alley cropping systems at Empire and Granada, MN. Error bars represent one standard error of the mean. Note different y-axis scales for each site

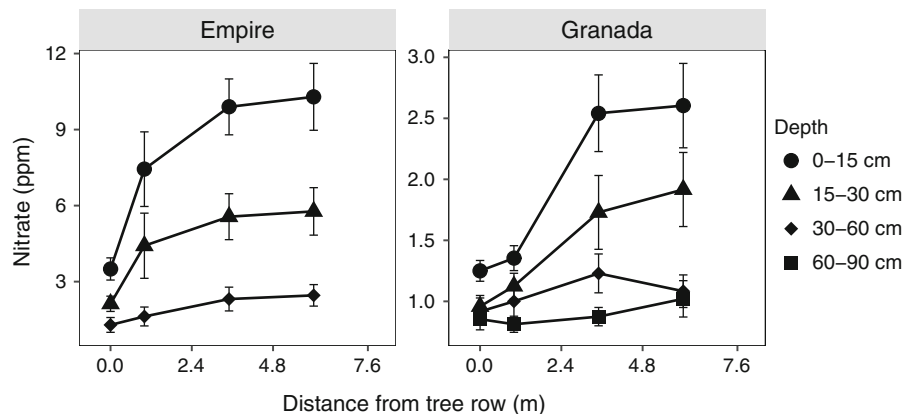


Table 6 Analysis of variance table of the full mixed effects model for 2013 herbaceous biomass yield at Empire, MN

Fixed effect	F val.	P (> F)
Water potential (A)	8.83	0.014
PAR (B)	11.04	0.011
Soil nitrate (C)	0.05	0.833
A × B	0.13	0.722
A × C	0.29	0.601
B × C	1.37	0.275
A × B × C	0.12	0.732

Table 7 Parameter estimates from best fitted mixed effects models for 2013 herbaceous biomass yield at Empire, MN

Site	Variable	β	SE(β)	<i>t</i> -value	<i>p</i> -value
Empire	Intercept	5.2058	0.9263	5.620	0.1389
	PAR	1.6568	0.6314	2.624	0.0233
	Water potential	0.9308	0.5153	1.806	0.0928

biomass yield. A mixed effects model that included terms for soil water potential and PAR best estimated herbaceous crop yield (Table 6). Including terms for soil NO₃-N and all two- and three-way interactions between water potential, PAR, and soil NO₃-N did not improve model fit.

Model estimated herbaceous biomass yield responded positively to increasing PAR and water potential. Over the range of observed PAR, model estimated crop yield varied by 3.7 Mg DM ha⁻¹. For every 100 μmol m⁻² s⁻¹ increase in PAR, model estimated herbaceous crop yield increased by 623 kg DM ha⁻¹ (Table 7). Over the range of observed water potential, model estimated crop yield varied by 5.2 Mg DM ha⁻¹. For every 20 kPa increase in average daily water potential, model estimated herbaceous crop yield increased by 1038 kg DM ha⁻¹. At Granada, no spatial variation in herbaceous crop yield was observed.

Discussion

Shrub willow—grassland alley cropping systems have shown short-term potential for biomass production, C

sequestration, and nutrient accumulation. However, long-term provision of these goods and services depends on the persistence and vigor of both the woody and herbaceous components of the system. We found that competition with willows for light and soil water at Empire substantially reduced prairie cordgrass and native polyculture biomass yield 2.4 m from tree rows, and had a moderate effect on yield up to 4.8 m from trees. In contrast, no spatial pattern in herbaceous crop yield was evident at Granada.

Soil nitrate

Compared to the alley center, soil nitrate-N in the 0–15 cm increment was reduced adjacent to tree rows by 66 and 52% (absolute differences of 6.8 and 1.3 ppm) at Empire and Granada, respectively. This was likely from increased N demand as a result willow fine roots extending into the herbaceous crop alley. However, N competition was not evident at either site. Competition for N is often found to be minimal or absent when standard rates of fertilizer N are applied in temperate alley cropping systems (Jose et al. 2000a; Miller and Pallardy 2001; Zamora et al. 2006). At Empire, prior biosolids additions resulted in high antecedent organic and inorganic N, which likely resulted in substantial mineralized N available to herbaceous alley crops despite competition with willow. At Granada, available soil N was lower than at Empire, though it can be inferred that N supply was sufficient since yields were similar across the entire alley.

PAR and alley orientation

A north–south alley orientation was detrimental to herbaceous crop growth in terms of light availability, whereas other alley orientations appeared to have no effect in this regard. The extent of shading throughout the day was greater at Empire than at Granada, which is consistent with our finding that competition for light reduced herbaceous crop yield at the former, but not the latter. This can largely be attributed to alley orientation, though tree LAI and D/H were greater at Empire than at Granada, and were consequently identified as significant sources of variation in relative PAR.

At Empire, there was a 57% reduction in PAR along the tree-crop interface (2.4 m) and a 21% reduction in

the center of the alley. Lin et al. (1999) found that many C_3 forage species can tolerate up to 50% shade without significant reductions in yield, while yields of C_4 forages were reduced under these conditions. At Empire, yields were reduced where PAR reduction exceeded 50%, even for C_3 intermediate wheatgrass (Gamble et al. 2016). At Granada, reduction in PAR was over 75% at the southern edge of the alley, but curiously, no reduction in yield was apparent. The reasons for this are unclear, though others have found that the effects of shading depend, in part, on the extent of belowground competition. For example, Gillespie et al. (2000) found that maize (*Zea mays* L.) yield was not impacted by up to 41% shade in black walnut (*Juglans nigra* L.) and red oak (*Quercus rubra* L.) alley cropping systems if belowground competition was eliminated with root barriers. One plausible explanation is that the shallow water table and proximity to high N-input annual agriculture were able to provide adequate water and N for both trees and crops, which could result in negligible effects of shading.

Soil water potential

Interestingly, competition for soil water influenced herbaceous crop yield at Empire. This was somewhat surprising given the shallow water table at this site and higher than average precipitation in 2013. However, hydrophytic species such as willow generally have high rates of evapotranspiration (ET) and low water use efficiency compared to both C_3 and C_4 perennial grasses (Jørgensen and Schelde 2001). Thus, high water use by willow reduced soil water availability to herbaceous alley crops in the zone of tree and crop root overlap.

We observed evidence of this during the summer at both sites, and also in fall at Granada. In willow-prairie cordgrass alleys at Empire, water potential was lower along the tree-crop interface relative to the center of the alley. Similarly, in willow-native polyculture alleys at Granada, water potential was reduced along the northern edge of the alley relative to the center. These patterns suggest that competition for soil moisture between willows and herbaceous crops will occur up to at least 2.4 m from tree rows in these alley systems, depending on seasonal water availability. However, average daily soil water potentials observed in this study never approached the permanent wilting point of -1500 kPa (Kirkham 2005).

Facilitative effects

Willows also played a facilitative role for herbaceous crops during certain periods at each site. For example, at Empire, higher water potentials adjacent to tree rows relative to the center of native polyculture alleys suggest plant water use was higher in the open than in the shelter of tree rows. Greater leaf area in the center of the alley partially explains these findings, as this likely resulted in greater ET at this position. However, we observed similar patterns in summer moisture availability at Granada with no differences in leaf area or biomass yield. Water potential in both native polyculture and prairie cordgrass alleys was greater along the southern edge of the alley than in the center. Thus, there was higher water use per unit leaf area in the center versus the southern edge of the alley, which suggests that trees played a facilitative role for both herbaceous crops under these circumstances. This could be a result of shading and/or reduced wind speeds along the tree-crop interface.

This finding is not surprising for the native polyculture, which contained a high proportion of C_3 species such as Canada wild rye (*Elymus canadensis* L.) and wild bergamot (*Monarda fistulosa* L.). Cool season (C_3) species can benefit from moderate shading and windbreak due to their low light saturation point and low water-use efficiency (Kephart et al. 1992; Lambers et al. 2008). In contrast, C_4 species such as prairie cordgrass have a higher light saturation point, a higher optimum temperature for photosynthesis, and greater water use efficiency than C_3 species (Kephart et al. 1992; Taiz and Zeiger 2010). This is evident in the fact that across sites, seasons, and alley positions, soil water potential was generally lower under native polyculture than prairie cordgrass plots in this study.

Management implications

Management interventions and alternative system designs could reduce competition in these systems and improve productivity. In similar climates and latitudes, perennial biomass alley systems should be planted to west–east or northwest–southeast alley orientations to minimize competition for light. Alternatively, if a north–south orientation is used, an alley width greater than 15.2 m would also reduce competition for light. However, this could result in lower alley system yields since the ratio of woody to

herbaceous crop area would decrease. Additional modifications such as utilizing agricultural subsurface tile drainage water, alternative harvest regimes, or evaluating additional woody and herbaceous crops should be considered to improve yield, on-farm utility, and ecosystem services from these systems.

Conclusions

Competition for light and soil water substantially reduced native polyculture and prairie cordgrass yield up to 2.4 m from willow rows at Empire, while at Granada, willows had no apparent effects on herbaceous crop yield. The relative impact of competition was similar for prairie cordgrass and a native polyculture at Empire, though the former had slightly higher yields overall. On average, a $100 \mu\text{mol m}^{-2} \text{ s}^{-1}$ increase in PAR resulted in a $623 \text{ kg DM ha}^{-1}$ increase in yield and a 20 kPa increase in average daily water potential resulted in a $1038 \text{ kg DM ha}^{-1}$ increase in yield. Light availability was lower in a north–south alley (Empire) than in west–east and northwest-southeast orientations (Granada), but shading appears to have played a facilitative role during the summer, resulting in reduced crop water use. Under similar climatic conditions, alley cropping systems comprised of shrub willow and herbaceous perennial biomass crops should avoid north–south row orientations to minimize shading.

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