Development of Agroforestry Systems for Bioenergy Crop Production and Soil Conservation

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Dedication

This thesis is dedicated to my daughter Signe Doviela, whose birth brought new joy to life, and whose smile brightens my day, every day.

Abstract

Agroforestry systems have been proposed as a means of dedicated bioenergy crop production that can potentially satisfy a broad suite of social, economic, and environmental objectives. Strategic placement of such systems may help to maximize economic returns from marginal crop land and reduce agricultural non-point source pollution. However, little is known about the performance of perennial bioenergy crops in agroforestry systems in the North Central Region. Moreover, the effectiveness of these crops in reducing certain types of agricultural non-point source pollution relative to conventional annual cropping systems is unknown. Therefore, experiments were conducted to 1) evaluate the establishment and productivity of dedicated woody and herbaceous perennial bioenergy crops in riparian alley cropping agroforestry systems, and 2) to evaluate the effects of dedicated perennial bioenergy crops on surface runoff and sediment loss relative to conventional and alternative annual cropping practices.

In the first experiment, basal area of poplar clone 'NM6' averaged 1,045 and 1,744 mm^2 $tree^{-1}$ at two sites after two seasons, while that of willow clone 'Fish Creek' averaged 770 and 1,609 mm^2 $tree^{-1}$. Prairie cordgrass and a native polyculture were among the most productive herbaceous crops at both sites, averaging between 7.1 and 11.9 Mt ha^{-1} by the second growing season. During the first two years following establishment, competition for resources did not reduce establishment success or productivity of woody and herbaceous crops along the tree-crop interface. These results suggest that hybrid poplar and willow along with certain herbaceous bioenergy crops may be well suited to alley cropping on riparian sites, though more research is needed to evaluate crop persistence and productivity within the alley cropping environment.

In the second experiment, a native grass mixture reduced the average sediment concentration in surface runoff by 87% and 90% relative to a corn-soybean rotation and no-till corn, respectively. Sediment concentrations in surface runoff from short-rotation willow did not differ from the corn-soybean rotation, but were reduced in fall surface runoff by 51% relative to no-till corn. These results suggest that soil conservation can be improved in short-rotation willow systems, but confirm previous findings that native grasses can provide excellent sediment retention relative to annual systems.

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1. INTRODUCTION

1.1 Bioenergy cropping systems and sustainability

State and federal mandates for renewable energy will expand markets for bioenergy, bioproducts, and biochemicals (Langeveld et al., 2010) and will require increased production of lignocellulosic feedstocks from agriculture (NRC, 2009). As a result, farmers will be presented with new opportunities to diversify their farming enterprise and improve economic return through the integration of bioenergy crops. Currently, much of the available supply of lignocellulosic feedstocks consists of residues from annual crops such as corn. However, the sustainability of this supply is in question due to concerns about soil erosion, water quality, and carbon sequestration (Blanco-Canqui, 2010; Tilman et al., 2006). Feedstocks derived from dedicated bioenergy crops offer clean energy alternatives to fossil fuels as well as environmental and economic advantages over those derived from annual crops.

Agroforestry has been proposed as an ecologically beneficial system for dedicated bioenergy crop production that can potentially satisfy a broad suite of social, economic, and environmental objectives (Holzmueller & Jose, 2012). Agroforestry systems that are designed to meet the demand for perennial biomass and bioproducts may also improve the sustainability of our agroecosystems by reducing risks for landowners and end-use facilities, improving economic returns, and meeting critical needs for ecosystem services.

1.2 Water quality and agriculture

Non-point source (NPS) pollution from agriculture has degraded water quality in much of the North Central Region of the United States (defined as: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, South Dakota, Wisconsin). Surface runoff from agricultural fields can cause significant losses of sediment, particle bound P, and other pollutants to surface waters (Ginting et al.,1998a, b), resulting in turbidity, eutrophication, reduced aquatic habitat quality, and reduced aesthetic and recreational values for lakes and rivers.

In Minnesota, agricultural nonpoint source pollution in the Minnesota River Basin (MRB) has received much recent press and is an issue of increasing public and regulatory concern. The 303(d) List of Impaired Waters currently contains over 100 water quality impairments for turbidity in the MRB (MPCA 2011), accounting for up to 90% of the annual downstream loading of 900,000 Mt of sediment in Lake Pepin and the upper Mississippi River (Engstrom et al., 2009; Kelley & Nater, 2000; James et al., 1997; Mulla & Sekely, 2009). Moreover, sediment deposition rates have increased by an order of magnitude since European settlement, with the majority of this increase occurring between 1940 and 1970 (Engstrom et al., 2009), a fact that strongly implicates modern agriculture as a contributing factor. While up to 40% of this sediment can be attributed to bluff and stream bank erosion as a result of increased flows (Sekely et al., 2002), surface soil erosion rates in upland areas have increased many times since the development of agriculture in the MRB (Mulla & Sekely 2009).

1.3 This project

Societal goals for renewable energy and improved water quality in agricultural areas may provide a unique opportunity for synergy. Bioenergy-based alley cropping systems planted in sensitive riparian areas in place of annual crops could help to meet societal objectives for water quality improvements, while potentially providing economic returns from marginal agricultural lands. However, little is known about the performance of dedicated bioenergy crops in alley cropping systems on riparian sites. Moreover, the effect these crops will have on sediment losses relative to conventional annual cropping systems in North Central Region is unclear.

Therefore, the objectives of this project are 1) to evaluate the establishment and productivity of dedicated woody and herbaceous perennial bioenergy crops in riparian alley cropping agroforestry systems and 2) to evaluate the effects of dedicated perennial bioenergy crops on surface runoff and sediment losses relative to conventional and alternative annual cropping practices. The following two chapters will specifically address these objectives.

2. ESTABLISHMENT OF PERENNIAL ALLEY CROPPING SYSTEMS FOR BIOENERGY CROP PRODUCTION

2.1 Introduction

The emerging bioeconomy has the potential to provide new opportunities for bioenergy crop adoption across the Midwest, as new sources of bioenergy feedstocks will be required to meet rising demand for fuel and fiber. However, it is critical to devise bioenergy feedstock production systems that can meet broad societal and environmental objectives in addition to providing the raw materials to fuel the bioeconomy.

Agroforestry, the intentional integration of woody perennials with crops or livestock, is a polyculture cropping strategy that can have economic and environmental benefits over that of traditional monoculture production systems (Jose, 2009). Alley cropping, one type of agroforestry, is the planting of crops between widely spaced rows of trees. Under certain circumstances, alley cropping systems can improve crop survival and yield, provide many environmental benefits, and improve economic returns. As a result, production of bioenergy crops in alley cropping systems may improve the sustainability of our agroecosystems, while providing new economic opportunities for producers.

2.1.1 Temperate alley cropping systems

Of the many agroforestry practices, alley cropping shows particular promise for temperate regions (Thevathasan & Gordon, 2004). Temperate alley cropping is typically defined as the interplanting of commodity or forage crops between widely spaced rows of trees or shrubs. Traditional applications of alley cropping in North America originated in pecan (*Carya illinoinensis* [Wangenh.] K. Koch) production and fruit orchard establishment in an effort to improve early economic returns using cash crops (Williams & Gordon, 1992). Recently, research with other hardwood and orchard trees such as black walnut (*Juglans nigra* L.), hybrid poplar (*Populus* spp.), or silver maple (*Acer sacharrinum* L.) has sought to expand applications for alley cropping (e.g. Garrett et al., 2000; Reynolds et al., 2007), resulting in systems that produce a variety of products, including high value veneer, saw logs, and wood pulp for the paper industry, in addition to orchard fruits and nuts, annual commodities, and animal forage. Common alley crops include grain crops such as corn (*Zea mays* L.) or soybean (*Glycine max* [L.] Merr.), or hay or forage crops such as alfalfa (*Medicago sativa* L.) or grass mixtures.

Alley cropping systems can improve crop survival and yield by providing more favorable growing conditions relative to monoculture systems (Jose et al., 2004). Microclimate modification by trees via moderate shading, reduced wind stress, hydraulic lift by tree roots, enhanced nutrient cycling, and improved moisture retention can create favorable growing conditions in alley cropping systems for some crops (Jose et al., 2004; Quinkenstein et al., 2009). In addition, differences in plant structure and function between tree and alley crops can provide opportunities to explicitly design systems to maximize resource use within a system and improve overall yield. Differences in plant rooting depth and habit, shoot morphology, growth phenology, and plant functional group can provide opportunities to facilitate beneficial interspecies interactions and maximize the use of spatial, temporal, and physical growth resources at a given site (Jose et al., 2000a). By mixing species with different life cycles and nutrient requirements, interspecies competition can de minimized, positive (mutualistic) or neutral (commensalistic) interactions can be facilitated, and overall biomass productivity and stability can be maintained relative to monoculture systems (Tilman & Downing, 1994). The success of alley cropping systems hinges on successfully managing these interactions between the tree and crop components.

In addition to production benefits, the incorporation of trees into agricultural systems can have many beneficial impacts on local environmental conditions. Improvements in air and water quality, non-point source pollution reduction, carbon sequestration, biodiversity conservation, and wildlife habitat have all been reported in alley cropping systems (Jose, 2009). In addition, alley cropping systems have been found to improve soil chemical, physical, and biological properties through additions of above- and below- ground tree litter and recycling of nutrients (Jose, 2009). Improvements in soil porosity and water infiltration (Udawatta et al., 2008a), soil organic matter (Olbermann et al., 2005), soil aggregate stability (Udawatta et al., 2008b), and carbon and nitrogen availability (Thevathasan & Gordon, 1997) are just a few notable examples.

2.1.2 Alley cropping with perennial bioenergy crops

To date, most bioenergy cropping systems have been focused on monoculture production of fast growing, high yielding herbaceous species such as switchgrass (*Panicum virgatum* L.) or *Miscanthus* spp. or woody species such as hybrid willow (*Salix* spp.) or poplar (*Populus* spp.). Surprisingly, relatively little information exists regarding alley cropping or other agroforestry systems designed to produce both woody and herbaceous bioenergy feedstocks. Colletti et al. (1994) suggest that production of herbaceous energy crops planted between rows of short rotation woody crops (SRWCs) can be productive and economically feasible in Iowa. However, the authors provided no experimental evidence of this. More recently, Holzmueller and Jose (2012) suggest that targeting bioenergy crop-based agroforestry systems, such as alley cropping, to riparian corridors in the North Central Region of the U.S. can potentially reduce non-point source stream pollution and sediment runoff while satisfying a portion of local energy demand. However, the authors note that little information exists regarding appropriate species combinations, rotation lengths, and long-term production potential of bioenergy crops in such systems.

2.1.2.1 Economic benefits

The deployment of new bioenergy crops across the landscape will provide a host of rural development benefits in the form of new jobs, infrastructure, and local markets (Proakis et al., 1999). However, production of bioenergy crops in agroforestry systems could further enhance these benefits for both producers and end-users of feedstocks. First, integrating both woody and herbaceous crops into biomass production systems will create a diverse feedstock supply and provide a consistent stream of raw materials throughout the year for end-users, which would enhance the economic feasibility of small scale conversion facilities or energy producers (Wright, 1994), and reduce the need for feedstock storage. For example, herbaceous crops could be harvested to meet fall and early winter biomass demands, while harvest of woody crops could be delayed until late winter or early spring. In this manner, the need for costly storage facilities is minimized and the potential for feedstock degradation during storage periods reduced (Forsberg, 2000; Paine et al., 1996).

Second, successful establishment of many perennial biomass crops can present a significant challenge, particularly for mixed species plantings (Mangan et al., 2011). It takes three years, on average, for native grassland plantings to establish and reach a level of sustained yield (van Ruijven & Berendse, 2005). During this time, environmental and climatic factors, weed competition, or pest damage can result in crop failure. Agroforestry systems can improve crop survival and yield under certain circumstances and may provide improved conditions for bioenergy crop establishment relative to monoculture systems. These improvements are facilitated via microclimate modifications such as reduced heat and wind stress, reduced evaporative loss, lower soil surface temperatures, and increased soil moisture due to moderate shading (Clinch et al., 2009; Jose et al., 2004; Quinkenstein et al., 2009). For example, Clinch et al. (2009) evaluated yields of three willow clones planted in alleys between rows of hardwood tree species in southern Ontario and found willow yields to be greater in the alley cropping system than in monoculture plantations. The authors attributed the increase in yields to a buffering effect providing by moderate shading, which reduced variation in soil moisture and temperature (Clinch et al., 2009). If these factors can be successfully exploited in a bioenergy crop-based alley cropping system, survival and yields can be improved and economic returns may increase.

Finally, under certain conditions alley cropping can reduce the need for external fertilizer inputs relative to monoculture systems, resulting in cost savings to a producer. Thevathasan and Gordon (1997) found that nitrification rates and N availability were higher close to poplar tree rows (< 2.5 m) than in the center of the alley (4-11 m from tree rows) as a result of poplar leaf litter inputs. This increased nutrient availability resulted in improved barley grain yield in rows close to poplar trees and reduced the need for external N fertilizer by 7 kg ha^{-1} (Thevathasan & Gordon, 1997). Furthermore, tree roots may also act as a "safety net" for nutrients which would otherwise leach below the root zone of crops, recycling them through leaf and root litter inputs to the soil and improving overall nutrient use efficiency (Jose, 2009). For example, Allen et al. (2004) found that a pecan-cotton alley cropping system retained 64% more nitrate-N than monoculture cotton.

2.1.2.2 Ecosystem benefits

Agroforestry systems that are intentionally designed to meet the demand for perennial biomass and bioproducts can also meet critical needs for ecosystem services, improving the sustainability of our agroecosystems. Improvements in air and water quality, non-point source pollution reduction, carbon sequestration, biodiversity conservation, and wildlife habitat have all been reported in alley cropping systems (Jose, 2009).

As mentioned previously, the "safety-net" effect of tree roots can improve nutrient cycling and overall nutrient use efficiency of agricultural systems. In doing so, alley cropping systems can reduce nutrient leakiness and inputs to groundwater (Jose, 2009). Moreover, additive or complementary effects of certain ecosystem services can be achieved in agroforestry systems. Lee et al. (2003) found that riparian buffers containing switchgrass (*Panicum virgatum* L.) and woody perennials were more effective at removing sediment and nutrients from runoff than buffers solely containing switchgrass. Similar multispecies buffer strips have been found to control up to 77% of soil bound phosphorus and 80% of nitrogen in surface runoff from adjacent row crops (EPA, 1995; Garrett et al., 2000).

Alley cropping systems have also been found to be more effective at sequestering atmospheric carbon in soils than sole crop systems (Bailey et al., 2009; Peichl et al., 2006). Peichl et al. (2006) found that a hybrid poplar-barley (*Hordeum vulgare* L.) alley cropping system sequestered 12 Mt C ha^{-1} yr^{-1}on a southern Ontario loam, whereas a barley monoculture resulted in net emission of 2.6 Mt C ha^{-1} yr^{-1}. This feature may make alley cropping systems an attractive option as the need for reducing agricultural C emissions becomes a more pressing issue.

Evidence that agroforestry systems can conserve and enhance floral, faunal, and soil microbial biodiversity is accumulating (Jose, 2012). Research has shown that relative to annual cropping systems, agroforestry systems can provide superior habitat for beneficial insects (Brandle et al., 2004) and avian species (Gillespie et al., 2005) and can also enhance landscape connectivity and reduce edge effects along conventional agricultural lands (Jose, 2009), depending on species selection and spatial arrangement.

Finally, increasing landscape diversity in agricultural areas via perennial bioenergy cropping can improve biological control of soybean aphid **(***Aphis glycines* Matsumura**)** (Gardiner et al., 2009)**,** an increasingly destructive agricultural pest in the Midwest. Increased vegetative diversity can also improve habitat for many species of bees (Gardiner et al. 2010), which are of the utmost ecological and economic importance for agriculture (Ratnieks & Carreck, 2010).

2.1.2.3 Minimizing competition for acres with food crops

Despite potential economic and environmental benefits, it is critical to devise bioenergy production systems that minimize competition for land area with food crops. Holzmueller and Jose (2012) suggest that marginal riparian land is ideal for biomass production in agroforestry systems. Riparian or lowland sites are prone to flooding, making them poorly suited for annual row crops during wet years but ideal for many perennial bioenergy crops (Thelemann et al., 2010). Many of these areas are currently enrolled in Federal "working lands" programs such as EQIP and CSP. As a result, biomass could be produced on these lands without taking additional agricultural land out of production (Holzmueller & Jose, 2012; Volk et al., 2004). Furthermore, targeting these systems to riparian acres will maximize environmental benefits by providing perennial vegetative buffers in ecologically sensitive corridors along streams, wetlands and other waterways.

2.1.3 This experiment

Bioenergy-based alley cropping systems planted in sensitive riparian areas could provide a unique opportunity to address multiple environmental, social, and economic objectives. However, improper species selection and crop spatial arrangement can result in poor crop establishment, reduced overall productivity, and ultimately crop failure due to competition for resources between trees and crops (Garrett et al., 2000).

Little is known about appropriate species combinations, planting arrangements, rotation lengths, and long-term production potential for bioenergy crops in alley cropping systems (Holzmueller & Jose, 2012). Given the lack of knowledge in this area, the objective of this study was to assess the suitability of selected woody and herbaceous perennial bioenergy crops for alley cropping systems at two riparian sites by evaluating crop establishment and productivity over the first two growing seasons.

2.2 Materials and Methods

2.2.1 Study Site and Design

The study was established in 2010 and data collected in 2010 and 2011 at two farms in Minnesota. Sites were near Granada, MN (43°45’28” N; 94°20’48” W), and Empire, MN (44°39’59” N; 93°06’39” W), hereafter referred to as the “Granada” and “Empire” sites, respectively. Soils at the Granada site 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 2.1). Soils at the Empire site 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. Soils at both sites range between 0 and 5% slope. The Granada site was in a long-term corn (*Zea mays* L.) – soybean (*Glycine max* [L.] Merr.) rotation and the Empire site in continuous corn. Repeated applications of municipal biosolids at Empire prior to establishment of the experiment resulted in greater organic matter and nutrient availability at this site compared to Granada. Flooding at Granada during 2010 and 2011 resulted in submergence for 36, 17, and 12 days for the three experimental replicates at this site, while at Empire, one experimental replicate was submerged for approximately 7 days due to flooding. 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 2.1: 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
Empire	Loam	964	236	5.5	5.2	8.98
Granada	Silty clay loam	36	114	6.4	3.6	11.96

†Samples were collected to 15.24 cm (6 in.) depth

Alley cropping systems consisted of herbaceous crops planted between multi-row strips of short rotation woody crops (SRWC). Herbaceous crops consisted of switchgrass (*Panicum virgatum* L.), prairie cordgrass (*Spartina pectinata* Bosc ex Link), a Pioneer Brand '54V48' alfalfa (*Medicago sativa* L.) and 'Rush' intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth and Dewey) mixture, and an eleven species native tallgrass-forb-legume polyculture. Hereafter, herbaceous treatments will be referred to as follows: SWG, PCG, AWG, and MIX for switchgrass, prairie cordgrass, alfalfa – intermediate wheatgrass, and the native polyculture, respectively. Woody crops were poplar hybrid 'NM6' (*Populus maximowiczii x P. nigra*) and willow hybrid 9882-42 'Fish Creek' (*Salix purpurea x S. purpurea*).

The experimental design was a randomized complete block in a full-factorial split plot arrangement. Three replicates were established at each site, with woody crops randomly assigned to whole plots and herbaceous crops randomly assigned to sub-plots within each whole plot. Whole plots measured 38.1 m by 36.6 m, and sub-plots measured 12.2 m by 9.1 m. Within each whole plot, multiple-row willow or poplar strips were separated by a 12.2 m alley; four sub-plots were nested within the alley between the woody crops (Figure 2.1). Alley orientation at Empire was North-South, while at Granada it was approximately Northeast-Southwest (replicates 1 and 2) and East – West (replicate 3). The relative allocation of land area within one replicate was 58% trees and 42% herbaceous crops.

Herbaceous crops were established by manual broadcast seeding, with the exception of prairie cordgrass, which was established from live rhizomes hand planted at 0.3 m x 0.3 m spacing. 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). 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 at St. Paul, MN. The mixture seeded in ALF was approximately 64% alfalfa and 36% intermediate wheatgrass, corresponding to seeding rates of 5.7 and 9.1 kg pure live seed (PLS) ha^{-1}. The native polyculture (MIX) 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, respectively (Table 2.2), and was seeded at 17.1 kg PLS ha^{-1}. Native legume seeds were scarified using a mechanical compressed air/sandpaper scarifier and were inoculated before planting using a modification of the recommendations of Tlusty et al. (2004), as directed by B. Tlusty (personal communication). Switchgrass was seeded at 18.2 kg PLS ha^{-1}.

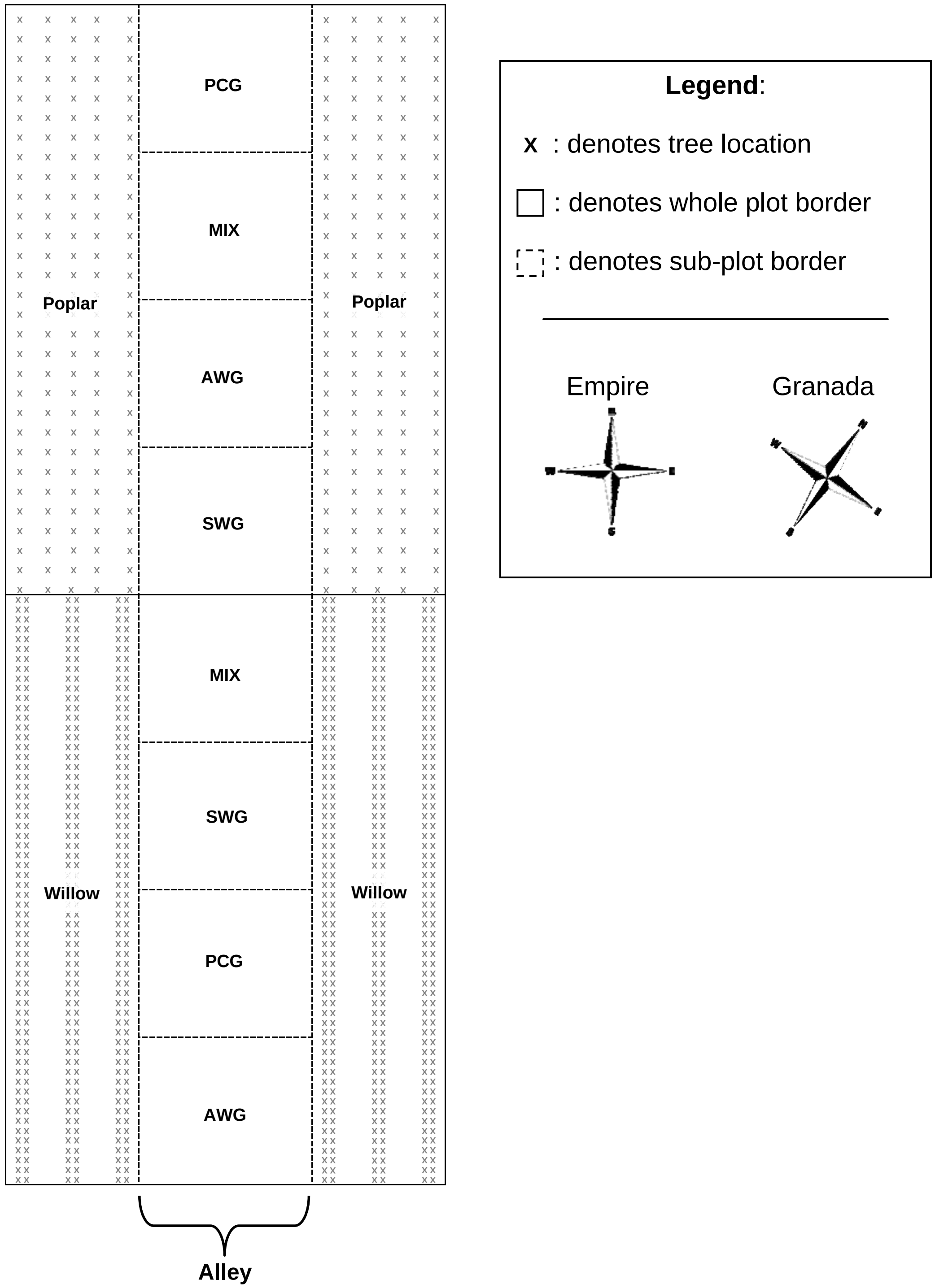

Figure 2.1: Example layout for one replicate of the split plot alley cropping system. Treatments were randomly assigned to whole and sub-plots within each replicate at each site. Treatment names are provided for illustrative purposes only.

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 the establishment season to control weeds, once in mid-July and once in late July or early August, except for PCG 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.

Table 2.2: Composition of the native polyculture (MIX) seeded in alley cropping systems at two Minnesota sites in May 2010

Botanical name	Common name	Functional group	Percent of mixture†
Andropogon girardii Vitman	Big bluestem	C_4 grass	61.6
Astragalus canadensis L.	Canada milk vetch	Legume	1.1
Chamaecrista fasiculata Michx.	Partridge pea	Legume	0.5
Dalea pupurea Vent.	Purple prairie clover	Legume	1.2
Desmodium canadense (L.) DC.	Showy tick-trefoil	Legume	1.1
Elymus canadensis L.	Canada wild rye	C_3 grass	10.7
Helianthus maximiliani Schrad.	Maximilian sunflower	Forb	2.9
Monarda fistulosa L.	Wild bergamot	Forb	4.5
Panicum virgatum L.	Switchgrass	C_4 grass	7.2
Ratibida pinnata (Vent.) Barnhart	Yellow coneflower	Forb	5.8
Symphyotrichum leave (L.) A. & D. Löve	Smooth blue aster	Forb	3.5

†Percent of mixture was calculated as the number of seeds per species per acre divided by the total number of seeds per acre. The sum of percentages is greater than 100 due to rounding.

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 stem cuttings were obtained from a commercial nursery (Double A Willow Inc., Fredonia, NY) 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, and 60 cm between plants within a row, and 150 cm between double rows, resulting in a density of 14,332 willows ha^{-1}. 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-diamin) shortly after planting for pre-emergent weed control. Willows were coppiced during dormancy following the first growing season to encourage the development of multiple stems, more rapid shoot growth, and rapid canopy closure (Abrahamson et al., 1998; Volk, 2002). Willows were cultivated in June 2011 for post emergence weed control, and will be harvested on three year rotations following coppice.

Unrooted 25 cm poplar stem cuttings were obtained from a commercial nursery (Lodholz North Star Acres, Inc., Tomahawk, WI) and were planted approximately 20 cm into the soil, leaving one or two buds above ground level. Poplars were established at 1.2 m within and between rows in a density of 6,670 plants ha^{-1} (Benomar et al., 2012; DeBell at al., 1996; DeBell et al., 1997) and managed in a single-stem system, i.e. plants were not coppiced (Hervé & Ceulmans 1996; Volk, 2002) and will be harvested at the biological rotation age. Manual weed removal was performed as needed in poplar plots.

In mid-June 2010, any dead or dying poplar and willow trees were replaced with fresh un-rooted tree stock to ensure adequate stocking.

2.2.2 Data collection & statistical analysis

All willow and poplar trees were counted in August 2010 (3 months after planting) and May 2011 (12 months after planting) at each site to determine plant survival. Poplar and willow plant heights, diameters, and stem counts were collected following plant senescence in 2011 and basal area per tree and per hectare were calculated for a subsample of trees.

Stem diameters were measured at a height of 30 cm for willow and at 140 cm (breast height) for poplar. The height of the tallest living stem in each plant was measured to the nearest inch (2.54 cm). Data was collected for n = 6 and n = 8 trees in two rows (2 x 3 trees and 2 x 4 trees) for willow and poplar, respectively, along the tree-crop interface (representing a tree/crop interaction) and in the center of the plot (representing little or no interaction) for each SRWC x herbaceous crop combination. Hereafter, these will be referred to as the "edge" and "center" row positions, respectively (Figure 2.2).

Establishment and botanical composition of herbaceous crops were assessed by counting the number of plants, by species, in three randomly selected 0.3-m^2 quadrates in each plot in mid July 2010 (prior to mowing) to determine crop and weed density, except for PCG, for which establishment was assessed by estimating percent survival of 9 plants in each of three randomly selected 1-m^2 quadrates in each plot in November 2010. Samples of the herbage in each sub-plot within the alley were harvested each fall following a killing frost or plant senescence to determine dry matter production.

In 2010, all plant material in three randomly selected 1-m^2 quadrates was harvested to a 10 cm stubble height at each of the two tree-crop interfaces in the alley (representing a tree-crop interaction) and three were harvested in the center of the plot, 6 meters from the interface (representing little or no interaction) for each treatment combination. Hereafter, these will be referred to as the alley "edge" and "center" positions, respectively, for herbaceous dry matter yield (Figure 2.2).

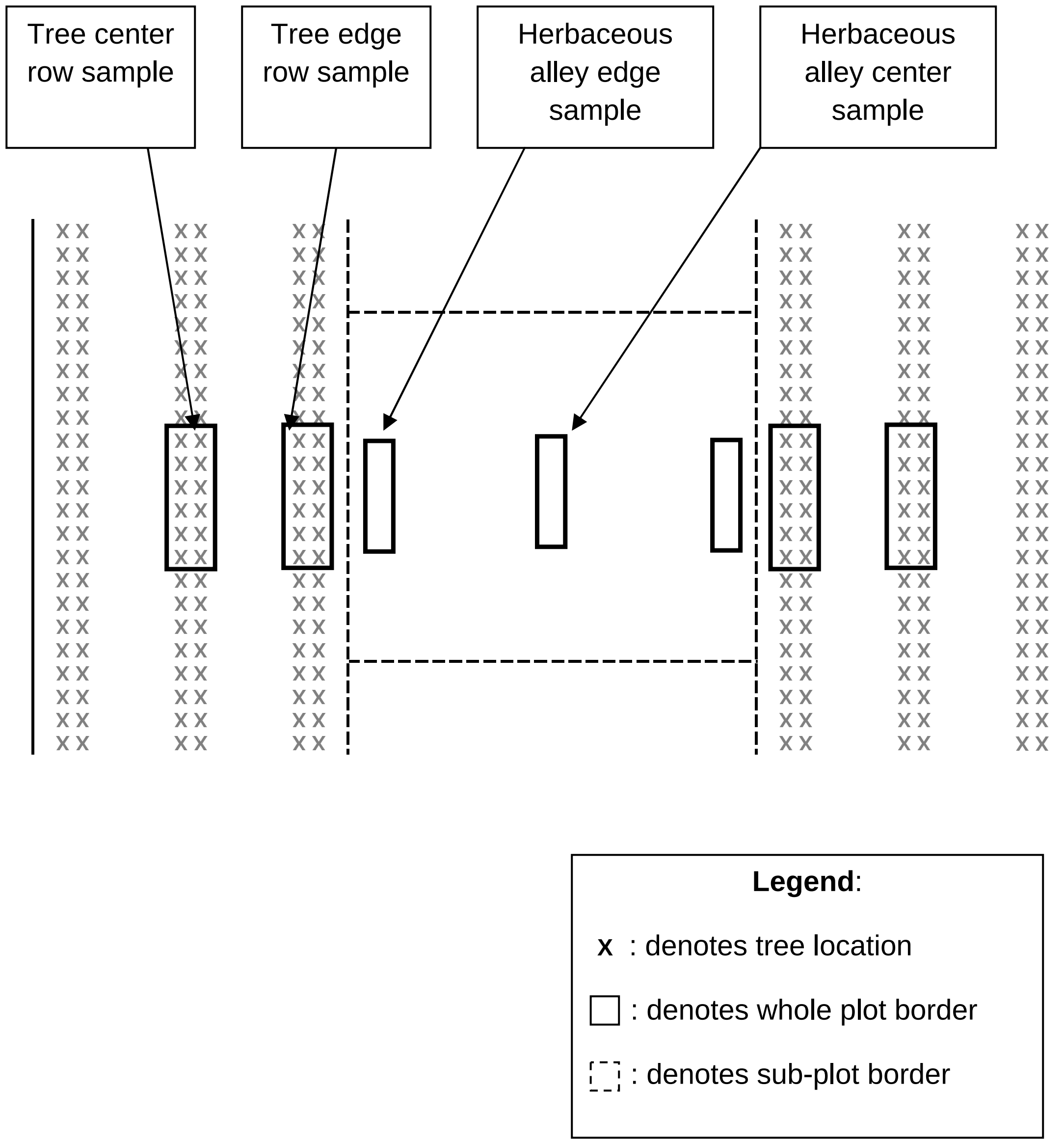

Figure 2.2: Sampling plot locations to assess potential differences in woody stand characteristics and herbaceous dry matter production relative to distance from the tree-crop interface. Woody stand characteristics were assessed on both sides of the alley.

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In 2011, all plant material in a 2.78 square meter area (0.91 m x 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 1000 g were dried in a 60º C oven to a constant weight and weighed again to obtain dry matter 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.

For tree heights, tree diameters, tree stem counts, herbaceous crop plant counts, and herbaceous dry matter yield, 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 versus center positions). Where interactions, treatment effects, and distance from the tree-crop interface were not significant, Student's t-test was used to test the significance of site. A mixed effects model was used to analyze per plant basal area, treating the whole plot error term as random. Variance components were estimated by REML (Patterson & Thompson, 1971), and approximate likelihood ratio tests using nested null and alternative hypothesis models were performed to verify the significance of components. For average basal area per hectare, the random effect for the whole plot error term added no explanatory value and was therefore omitted. As a result, average basal area per hectare data was analyzed using fixed effects ANOVA. 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. To test hypotheses, the following linear additive model was considered:

$$Y_{ijk} = \mu + \rho_i + \tau_j + \delta_{ij} + \beta_k + (\tau\beta)_{jk} + X_m + X_n + (\tau X)_{jm} + (\tau X)_{jn} + (\beta X)_{km} + (\beta X)_{kn} + (\tau XX)_{jmn} + (\beta XX)_{kmn} + e_{ijk}$$

Where:

Y_{ijk} : observation corresponding to the k[th] level of sub-plot factor (β), j[th] level of main plot factor (τ), and the i[th] replication (ρ).

μ : general mean

ρ_i : i[th] block effect

τ_j : j[th] whole plot treatment effect

β_k : k[th] sub-plot treatment effect

$(\tau\beta)_{jk}$: interaction between the j[th] level of whole plot treatment and k[th] level of sub- plot treatment.

X_m : m[th] effect of distance from the tree-crop interface

X_n : n[th] effect of site

$(\tau X)_{jm}$: interaction between the j[th] level of whole plot treatment and m[th] level of distance from the tree-crop interface

$(\tau X)_{jn}$: interaction between the j[th] level of whole plot treatment and n[th] level of site

$(\beta X)_{km}$: interaction between the k[th] level of sub-plot treatment and m[th] level of distance from the tree-crop interface

$(\beta X)_{kn}$: interaction between the k[th] level of sub-plot treatment and n[th] level of site

$(\tau XX)_{jmn}$: interaction between the j[th] level of whole plot treatment, m[th] level of distance from the tree-crop interface, and the n[th] level of site

$(\beta XX)_{kmn}$: interaction between the k[th] level of sub-plot treatment, m[th] level of distance from the tree- crop interface, and the n[th] level of site

The whole plot and experimental error terms, δ_{ij} and e_{ijk}, respectively, are independent and normally distributed with means zero and respective variances σ^2_δ and σ^2_e. The hypotheses tested were as follows:

1. H_0: No difference in average basal area per plant and average basal area per hectare between poplar and willow.
2. H_0: No effect of the adjacent alley crop (sub-plot) on average basal area per plant between and within both woody crops (i.e. no effect of tree row position).
3. H_0: Within each woody crop, no effect of the adjacent alley crop (sub-plot) on stem diameter, height or stem count (i.e. no effect of tree row position).
4. H_0: No difference in plant counts, weed biomass or dry matter production between herbaceous alley crops.
5. H_0: No effect of the adjacent woody crop (whole plot) on dry matter production of herbaceous alley crops (i.e. no effect of distance from the tree-crop interface)
6. H_0: No effect of site on woody or herbaceous crop characteristics or productivity

2.3 Results

2.3.1 Short rotation woody crops

2.3.1.1 Survival

Survival was greater than 95% for both willow and poplar, with the exception of the poplar stand at Granada in May 2011 (Table 2.3). A 3.1% decline in poplar survival at Granada from August 2010 to May 2011 was likely due to poplar mortality in one replicate that was more affected by repeated flooding than the other replicates at the site. When averaged across sites, there was a slight decline in poplar survival and nearly no change in willow survival from August 2010 to May 2011. Survival was similar for both woody crops by May 2011.

Table 2.3: Short rotation poplar and willow survival† three and twelve months after establishment in alley cropping systems at two Minnesota sites

	NM6 poplar		Fish Creek willow	
Site	**August 2010**	**May 2011**	**August 2010**	**May 2011**
	%			
Granada	95.0	91.9	95.8	95.4
Empire	98.1	97.9	96.4	96.4
Mean	*96.6*	*94.9*	*96.1*	*95.9*

†Survival rates are based upon the entire population of trees of each species at each site, N_{poplar} = 450 and N_{willow} = 1,080 were planted at each site in May 2010.

2.3.1.2 Plant height and stems per plant

Analysis of poplar plant height, stem diameter, and number of stems per plant showed no effect of the adjacent alley crop or row position. However, poplar stem diameter was greater at Empire than at Granada, as was average plant height (Table 2.4).

There was no difference between the average number of poplar stems in edge and center rows at Granada, whereas trees in edge rows had a greater number of stems than those in center rows at Empire. Poplar trees in both edge and center rows at Empire had a greater number of stems than those at Granada.

Analysis of average willow heights and number of stems per tree showed no effect of the adjacent alley crop or row position. However, average willow tree height was greater at Empire than at Granada with 337 and 296 cm, respectively. The average number of stems per willow tree was also greater at Empire than at Granada at 21.8 and 13.0 stems, respectively.

Table 2.4: Stand characteristics for alley cropped NM6 hybrid poplar at two Minnesota sites in the year following establishment

	Means†		
Site	**Plant height (cm)**	**Stems per plant**	
		Edge row	*Center row*
Empire	556.2 a	2.43 a	1.99 b
Granada	513.6 b	1.51 c	1.49 c

†For plant height, means in the same column followed by the same letter are not significantly different based on Student's t-test; $t\ (571) = 6.80$, $p < 0.001$. For "stems per plant", means in the same column and row followed by the same letter are not significantly different based on Tukey's HSD (0.01).

2.3.1.3 Average basal area per tree

Basal area ranged from 770 to 1807 mm^2 $tree^{-1}$ after two seasons, with interaction effects between site and row position, as well as site and species. When averaged across species, average basal area per tree was greater in edge rows than center rows at Empire, whereas at Granada, the opposite was true (Figure 2.3A). Average basal area per tree in edge and center rows was greater at Empire than at Granada. No difference was found between willow and poplar trees at Empire, whereas at Granada, poplar trees had greater average basal area than willow trees (Figure 2.3B). Basal area per tree was greater at Empire than Granada for both willow and poplar.

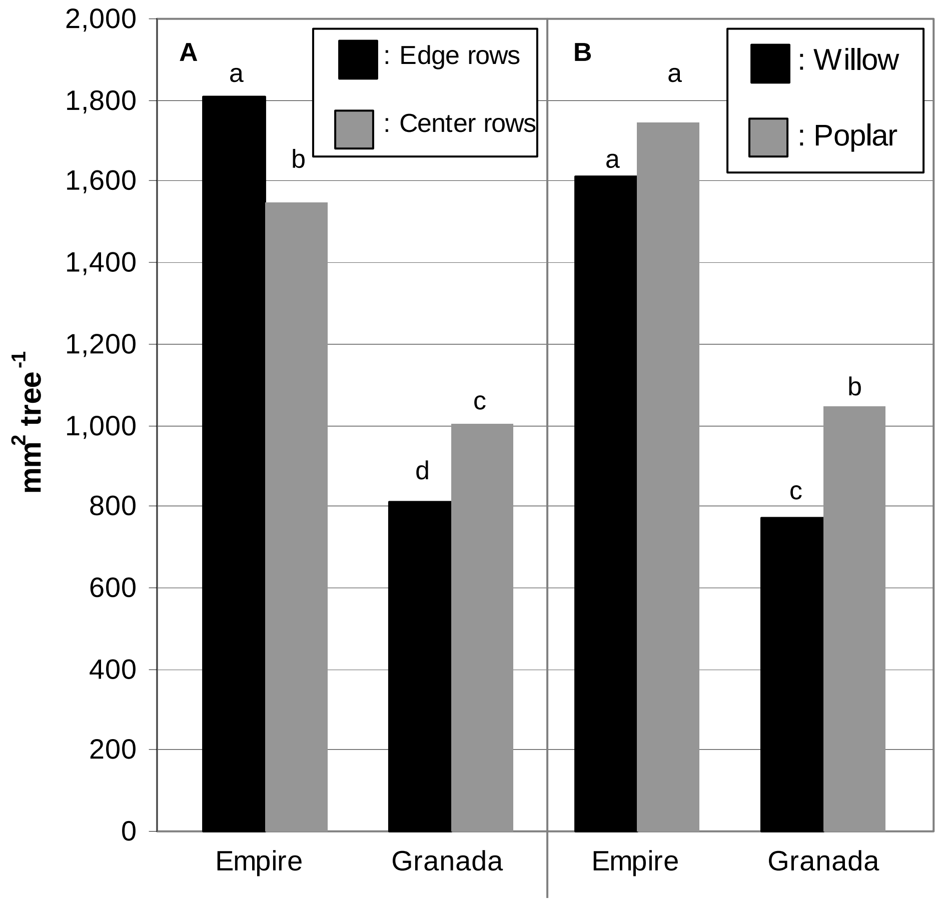

Figure 2.3: Average basal area per tree for alley cropped short rotation woody crops at two Minnesota sites in the year following establishment **A**) in edge and center rows and **B**) by species. Within each panel, bars with the same letter are not significantly different based on Tukey's HSD (0.05).

2.3.1.4 Average basal area per hectare

Average basal area per hectare after two seasons ranged from 6.7 to 25.5 $m^2\ ha^{-1}$, with interactions between site and row position and site and species. When averaged across species, edge rows had greater average basal area per hectare than center rows at Empire, whereas at Granada, no difference was found (Figure 2.4A). Average basal area per hectare in edge and center rows was greater at Empire than at Granada and was greatest for willow at Empire, followed by poplar at Empire, willow at Granada, and poplar at Granada (Figure 2.4B). Basal area per hectare was greater at Empire than Granada for both willow and poplar.

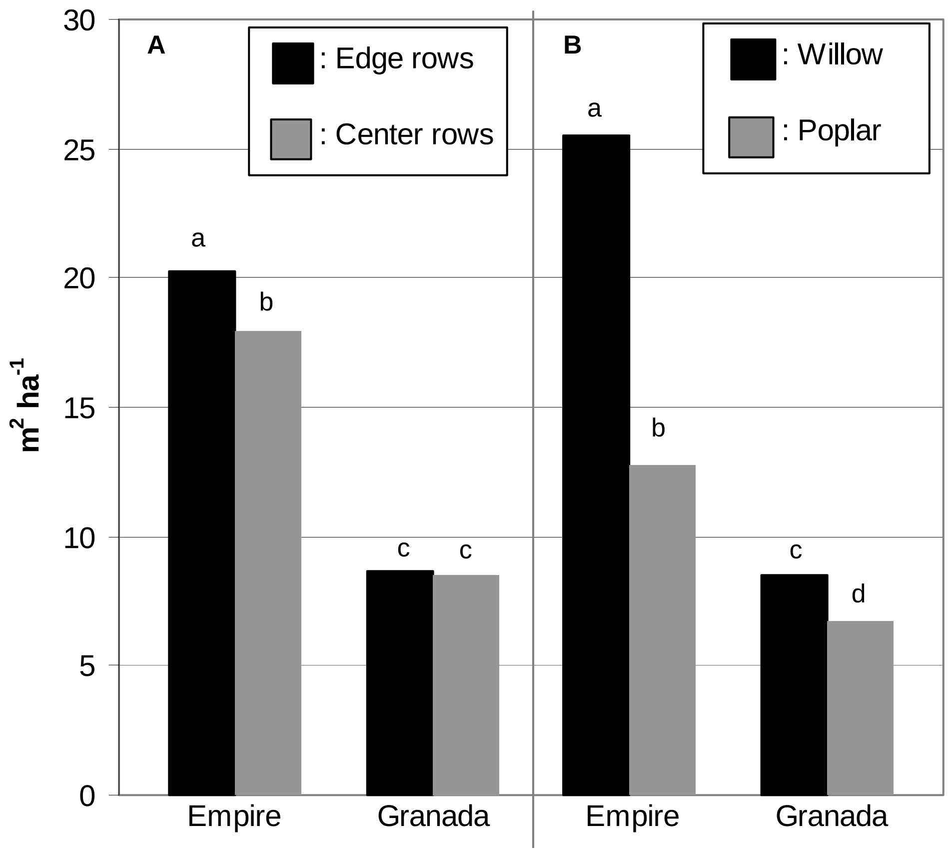

Figure 2.4: Average basal area per hectare for alley cropped short rotation woody crops at two Minnesota sites in the year following establishment **A**) in edge and center rows and **B**) by species. Within each panel, bars with the same letter are not significantly different based on Tukey's HSD (0.05).

2.3.2 Herbaceous alley crops

2.3.2.1 Plant density, composition, ground coverage, and survival

There were more switchgrass plants and less weeds per square meter for SWG at Granada than at Empire 45 days after seeding, but no differences in crop and weed density between sites for AWG and MIX (Figure 2.5). Crop plant density was greater for SWG and AWG than for MIX at both sites, whereas weed density did not differ between treatments at each site. Switchgrass (SWG) at Granada had the highest crop plant density of all treatments at both sites, while MIX at Empire and Granada had the lowest crop plant densities. In November 2010, plant survival in PCG was greater at Empire than Granada at 93% and 82%, representing 8.4 and 7.4 plants per m^2, respectively.

Intermediate wheatgrass (C_3 grass) comprised 50 – 56% of AWG compared to 34 – 38% for alfalfa (legume) 45 days following seeding (Table 2.5). Excluding weeds, intermediate wheatgrass and alfalfa comprised 60% and 40% of crop individuals, whereas the composition of the original seed mixture for AWG was 36% and 64%, respectively. Switchgrass (C_4 grass) was the predominant species in SWG, comprising 77% and 93% of individuals at Empire and Granada, respectively. Warm season (C_4) grasses were the largest component of MIX at both sites comprising 35 – 39% of individuals, with either C_3 grasses or broadleaf weeds as the second largest component. Legumes comprised 7 – 10% of individuals in MIX, forbs comprised 8% of individuals in MIX at Empire, and no forbs were observed at Granada.

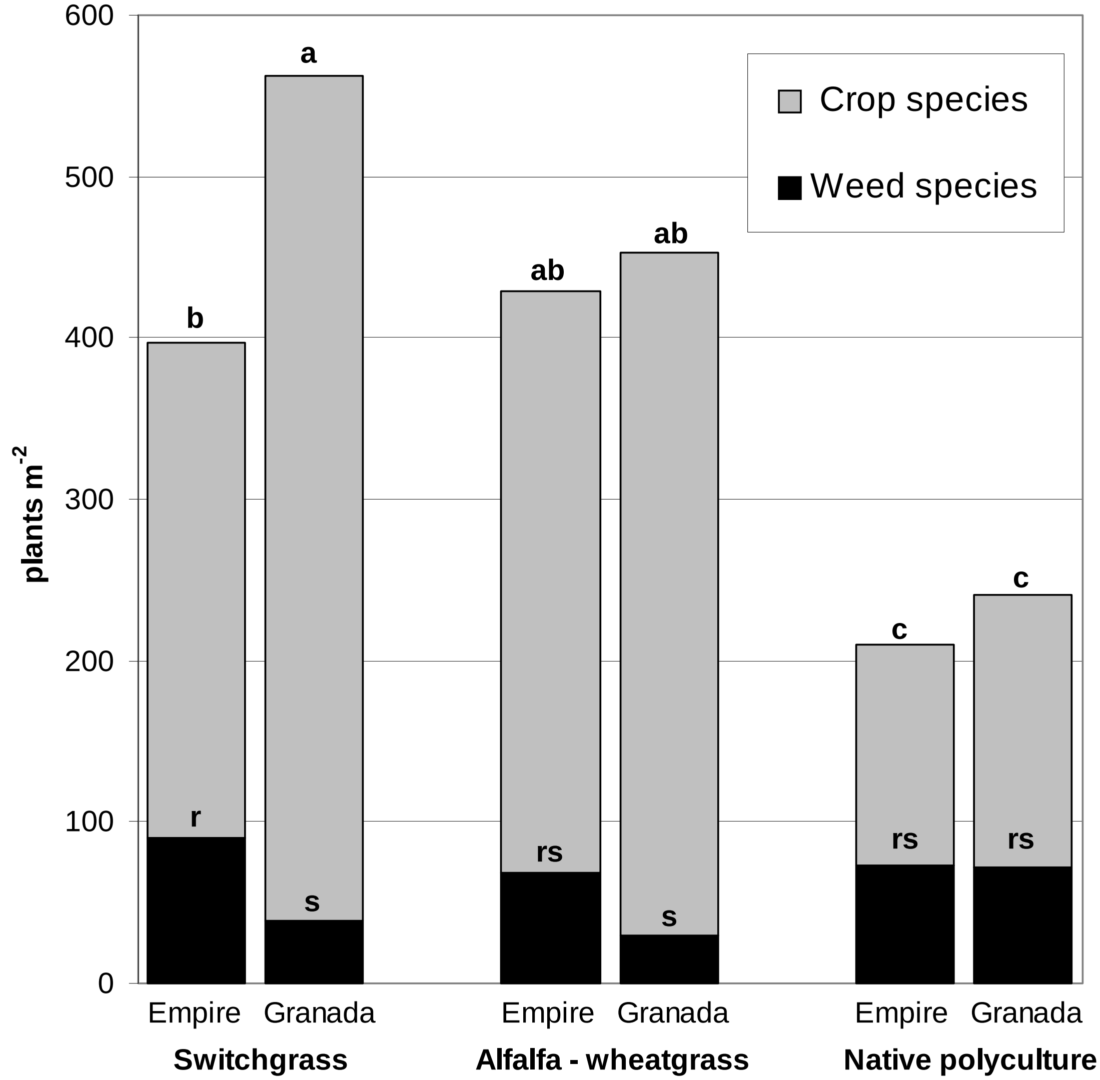

Figure 2.5: Average crop and weed density for three herbaceous alley crops at two Minnesota sites 45 days after seeding. Bars with the same letter are not significantly different based on Tukey's HSD (0.05). Letters a – c are used to denote differences between numbers of crop plants, while letters r – s are used to denote differences between numbers of weed plants between treatments and sites.

Weed composition was predominantly broadleaves at Empire, while at Granada, grass and broadleaf weed composition was similar, except for MIX, in which there was a larger proportion of broadleaves than grass weeds. The proportion of weeds was highest in MIX plots, at 30 – 34% of individuals across both sites.

Composition of the original seed mixture for MIX was approximately 69% C_4 grasses, 11% C_3 grasses, 17% forbs, and 5% legumes. When weeds were excluded from counts, composition of MIX plots after 45 days differed from the composition of the original seeded mix with C_4 grasses comprising 50 – 60% of crop individuals, C_3 grasses comprising 17 – 36%, forbs comprising 0 – 12% and legumes comprising 11 – 14%. Of the 11 species seeded in MIX, nine were observed at Empire while only seven were observed at Granada 45 days after seeding. Smooth blue aster (*Symphyotrichum leave* [L.] A. & D. Löve) and Maximillian's sunflower (*Helianthus maximiliani* Schrad.) were not observed at either site and wild bergamot (*Monarda fistulosa* L.) and yellow coneflower (*Ratibida pinnata* [Vent.] Barhart) were not observed at Granada.

Table 2.5: Botanical composition of three herbaceous alley crops at two Minnesota sites in July 2010, 45 days after seeding.

		Crop species				Weeds	
Site	**Treatment**	**C_3 grasses**	**C_4 grasses**	**Forbs**	**Legumes**	**Grasses**	**Broad - leaves**
		%					
Empire	SWG	NA [†]	77 (1) [‡]	NA	NA	3 (1)	20 (1)
	AWG	50 (3)	NA	NA	34 (2)	1 (1)	15 (2)
	MIX	11 (1)	39 (1)	8 (1)	7 (1)	1 (1)	33 (1)
Granada	SWG	NA	93 (6)	NA	NA	3 (1)	3 (1)
	AWG	56 (6)	NA	NA	38 (4)	2 (1)	4 (1)
	MIX	25 (2)	35 (1)	0	10 (1)	6 (1)	24 (3)

[†] NA: Not applicable; no species of this functional group were seeded into the treatment
[‡] Means are presented followed by standard errors in parentheses

By fall of 2011, ground cover in MIX plots at Empire was predominantly Canada wild rye (*Elymus candensis* L.), a C_3 grass, while at Granada coverage was nearly equally distributed between C_3 grasses, C_4 grasses, and forbs (Table 2.6). Legumes in AWG and MIX were scarce at Empire, while at Granada, legumes occupied 10% of MIX plots but were absent from AWG. Weeds were the predominant ground cover in AWG at Granada. At Empire, weed species represented a majority of the ground cover in the SWG plots, while at Granada, switchgrass was the predominant ground cover in SWG plots. In PCG plots, prairie cordgrass provided the majority of ground cover at both sites, occupying about 90% of ground area. At both sites, crop ground cover was greatest in MIX plots at 95% and 98% coverage at Granada and Empire, respectively.

Table 2.6: Percent ground cover by functional group for four herbaceous alley crops at two Minnesota sites in October 2011 following the second growing season

Site	Treatment	C_3 grasses	C_4 grasses	Forbs	Legumes	Weeds	Total
		%					
Empire	SWG	NA [†]	40 (7) [‡]	NA	NA	58 (7)	98
	AWG	94 (1)	NA	NA	3 (1)	3 (1)	100
	MIX	87 (3)	0	9 (1)	2 (1)	2 (1)	100
	PCG	NA	92 (1)	NA	NA	8 (1)	100
Granada	SWG	NA	86 (4)	NA	NA	14 (4)	100
	AWG	27 (9)	NA	NA	0	70 (9)	97
	MIX	29 (1)	28 (1)	28 (1)	10 (1)	5 (1)	100
	PCG	NA	88 (2)	NA	NA	12 (2)	100

[†] NA: Not applicable; no species of this functional group were seeded into the treatment
[‡] Means are presented followed by standard errors in parentheses

2.3.2.2 Weed biomass

In 2010, there were no differences in weed biomass between herbaceous crops at Empire, whereas at Granada, MIX and AWG had greater weed biomass than PCG and SWG (Table 2.7). The native polyculture (MIX) had more weed biomass at Granada than at Empire, while no other treatments differed in weed biomass between sites.

In 2011, SWG had more weed biomass than all other treatments at Empire, whereas at Granada, AWG had more weed biomass than all other treatments. No differences in weed biomass were found between PCG, AWG, and MIX at Empire, or between SWG, PCG, and MIX at Granada. Between sites, SWG had more weed biomass at Empire than at Granada, while AWG had more weed biomass at Granada than at Empire. No other treatments differed in weed biomass between sites.

Table 2.7: Weed biomass for four herbaceous alley crop treatments at two Minnesota sites for two years following establishment.

	2010†				2011			
Treatment	**Empire**		**Granada**		**Empire**		**Granada**	
	Mt ha^{-1}							
Native polyculture	0.82	a s‡	1.49	a r	0.10	b r	0.16	b r
Alfalfa – wheatgrass	0.90	a r	1.24	a r	0.13	b s	1.15	a r
Prairie cordgrass	0.43	a r	0.25	b r	0.40	b r	0.49	b r
Switchgrass	0.53	a r	0.23	b r	1.96	a r	0.45	b s

† In 2010, plots were mowed twice, except for prairie cordgrass which was moved once and hand weeded once. No weed control was used in 2011.
‡ Within the same year, means in the same site (column) or row (crop) followed by the same letter are not significantly different based on Tukey's HSD (0.05). Letters a – b are used to distinguish within site (column) differences, while letters r – s are used to distinguish within crop (row) differences.

2.3.2.3 Herbaceous alley crop dry matter yield

In 2010, dry matter yields ranged from 3.0 to 7.0 Mt ha^{-1}. Yields of ALF, MIX, and SWG at Granada did not differ but were greater than that of PCG (Figure 2.6A). At Empire, no differences in dry matter yield were found among herbaceous alley crop treatments. Furthermore, no differences in yield were observed between sites for any of the herbaceous crops. There was no effect of alley position or adjacent SRWC on average dry matter yields of alley cropped herbaceous biomass in 2010.

In 2011, dry matter yields ranged from 1.7 to 11.9 Mt ha^{-1}. At Granada, yield was lowest in AWG compared to all other treatments, and PCG yield was greater than SWG, but did not differ from MIX (Figure 2.6B). At Empire, MIX yield did not differ from PCG, but was greater than that of AWG and SWG. Prairie cordgrass (PCG) and AWG yields were not different, and SWG yielded less than all other treatments at the site. Between sites, MIX and AWG yields were greater at Empire than at Granada, whereas the opposite was true for SWG, and PCG yields did not differ between sites. As in 2010, there was no effect of alley position or adjacent SRWC on average dry matter yields of alley cropped herbaceous biomass in 2011. At Empire, average dry matter yield was greater in 2011 than in 2010, whereas no difference between years was found for Granada.

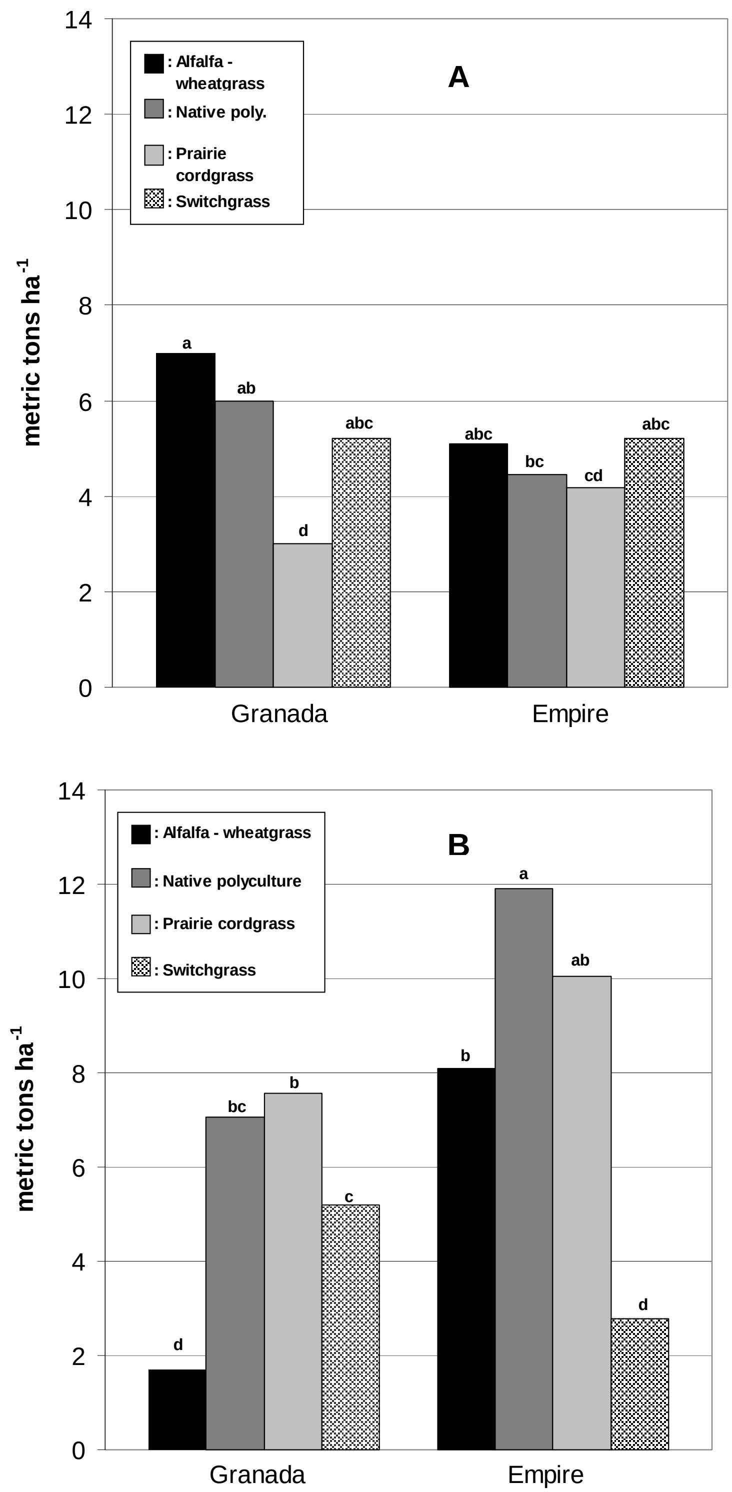

Figure 2.6: Dry matter yields for four herbaceous bioenergy alley crops at two sites in Minnesota in **A**) 2010, the establishment year and **B**) 2011, the year following establishment. Within each year, bars with the same letter are not significantly different based on Tukey's HSD (0.05).

2.4 Discussion

2.4.1 Woody crops

Poplar and willow survival were excellent at both sites, despite some poplar mortality at Granada due to flooding. Establishment year survival of less than 80% is considered unsuccessful for SRWC (Bergkvist et al., 1996). At greater than 90% survival at both sites, both poplar and willow establishment can therefore be considered successful. There were clear sites effects for all responses measured for SRWC with poplar and willow growth being superior at Empire compared to Granada. Frequent flooding at Granada during the first year of the study as well as higher nutrient availability at Empire are likely the primary factors that resulted in differences in crop growth between sites.

Site factors may also be responsible for a lack of difference in basal area per tree between SWRC at Empire and greater basal area per tree for poplar than willow at Granada. At Empire, no difference in basal area per tree was detected between the two SRWC, suggesting that perhaps the willow had a stronger growth response than the poplar to the high nutrient availability at this site. At Granada, the study period was marked by higher than average precipitation in spring and fall 2010 and spring 2011 that resulted in extreme flood events at the Granada site and throughout the Minnesota River Basin. Over the course of the first two growing seasons, it is estimated that one replicate at Granada was fully or partially submerged for 36 days, while the other two replicates were submerged for approximately 17 and 12 days. Visual observation of the trees in the most frequently flooded replicate clearly indicated poorer survival and growth of poplar than willow and poorer survival than in less frequently flooded replicates for poplar. Despite this, poplar had greater basal area per tree than willow when all trees at Granada were considered. Therefore, the difference in basal area between poplar and willow trees in less frequently flooded replicates of Granada was greater than the overall results for all three replicates would suggest. Over the following two years of the woody crop rotation, the frequency and duration of flooding at Granada will likely have a strong influence on which SRWC is the most productive at this site.

Currently, it appears that the high density Fish Creek willow coppice system may be better suited to these riparian planting sites and perhaps the alley cropping environment than the non-coppiced NM6 poplar clone system. However, planting density largely affected per hectare estimates of plant productivity. Poplar had greater basal area per tree than willow at both sites, however, a planting density of more than double that of poplar resulted in greater basal area per hectare for willow at both sites. It will be interesting to see if differences in per plant and per hectare estimates of productivity persist through the remainder of the first four-year rotation. Volk (2002) found that with identical planting densities, NM6 poplar produced more biomass than a variety of willow clones at three sites in New York by the end of a four year rotation. This suggests that poplar might be competitive with willow at Granada, where the difference in basal area per hectare between SRWC was small compared to that at Empire, despite differences in planting density.

2.4.2 Herbaceous crops

Establishment was excellent for all herbaceous crops except SWG at Empire and AWG at Granada. Crop plant density after 45 days indicated that germination and emergence was 60 - 86%, 80%, and 30% of seeded rates for SWG, AWG, and MIX, respectively. Despite lower crop density in MIX than other crops, weed density in this treatment did not differ from other crops. Furthermore, estimates of ground cover and productivity for this crop were among the highest for all treatments at both sites by fall 2011. As with SRWC, there were clear site effects for all responses measured for herbaceous crops. By 2011, biomass dry matter production was greater at Empire than Granada for all herbaceous alley crops except Switchgrass, in which weed pressure was higher at Empire than at Granada. At Granada, frequent flooding resulted in thin alfalfa and intermediate wheatgrass populations, resulting in poor productivity for AWG at this site by 2011. In contrast, prairie cordgrass thrived in the wet conditions at Granada, and had greater than 80% survival at both sites, resulting in PCG being among the most productive crops at each site.

Weed pressure at Empire resulted in SWG having greater weed biomass and lower crop biomass than all other treatments at the site by fall 2011. However, switchgrass yields averaged 2.8 and 5.2 Mt ha^{-1} at Empire and Granada, respectively. This compares reasonably well to the results of Mangan et al. (2011), who reported second year yields of native sourced switchgrass as high as 8.5 Mt ha^{-1} under ideal conditions (Lamberton, MN) and as low as 0.2 Mt ha^{-1} under extreme weed pressure (St. Paul, MN). In 2011, prairie cordgrass biomass yields were 10.1 and 7.6 Mt ha^{-1} at Empire and Granada, respectively. These results compare favorably to those of Boe and

Lee (2007), who reported second year yields of prairie cordgrass to be 6.0 Mt ha^{-1} in eastern South Dakota, and also Boe et al. (2009) who reported yields of mature (4 – 10 years) 'Red River' prairie cordgrass to be 12.6 Mt ha^{-1} in eastern South Dakota. Similarly, MIX yields compared favorably to other published accounts for native polycultures. In 2011, biomass yields of MIX were 11.9 and 7.1 Mt ha^{-1} at Empire and Granada, respectively. Mangan et al. (2011) found yields of a similar native polyculture ranged between 1.5 and 6.9 Mt ha^{-1} across 8 Minnesota sites. Lastly, in 2011 AWG yielded 1.7 and 8.1 Mt ha^{-1} at Granada and Empire, respectively. These yields are both less than those of Sleugh et al. (2000), who reported that an alfalfa-intermediate wheatgrass mixture yielded 12.7 Mt ha^{-1} in the year following establishment in central Iowa. However, Sleugh et al. (2000) conducted four harvests throughout the growing season to estimate yield, in contrast to the single-cut fall harvest used in this study.

The native polyculture was among the highest yielding crops at both sites in both years. This is a bit surprising given the typically slow establishment of native grassland plantings (van Ruijven & Berendse, 2005). However, at Empire, nearly 90% of ground cover in MIX plots was Canada wild rye (*Elymus candensis* L.), an early successional C_3 grass. At Granada, about 30% of ground cover in MIX plots was Canada wild rye, despite comprising only 11% of the seeded mixture. This predominance of Canada wild rye can perhaps be explained by its status as an early successional species, its cool-season growth phenology, and at Empire, high nutrient availability. Pywell et al. (2003) found that high levels of soil nutrients may result in polycultures dominated by only a few highly competitive species. Furthermore, in native tallgrass prairie rangelands, spring fertilization can result in increased presence of cool season (C_3) species, resulting in declines in other functional groups over time (Rehm et al., 1976; Pan et al., 2010). This predominance of a cool season grass likely also provided good suppression of spring annual weeds, as early, rapid, and dense ground cover provided by Canada wild rye would limit opportunities for weed seed germination and emergence. Thus, high levels of soil fertility and the resulting prevalence of Canada wild rye may explain why MIX dry matter production was among the highest at both sites by 2011.

2.4.3 The alley cropping system

During the first two years following establishment, competition for resources along the tree-crop interface did not reduce growth characteristics or basal area of SRWC. Conversely, an apparent edge effect at Empire resulted in a greater number of poplar stems in edge rows than in center rows, thereby increasing average basal area per hectare in edge rows relative to center rows. Species in the *Populus* genus are generally shade intolerant, primary successional species (Baker, 1949; Demerritt, 1990) that exhibit reduced shoot growth in shade (DeByle et al., 1985; Farmer, 1963). Light is an important factor promoting the development of shoots from buds in *Betula* (Kauppi et al., 1998) and *Salix* species (Paukkonen et al., 1992; Volk, 2002), and presumably also for *Populus* species. Ek et al. (1983) found that increased plant spacing resulted in an increased number of shoots for a variety of coppiced poplar hybrids, which supports the assertion that increased light availability can result in the production of additional stems in *Populus* species. Thus, proximity to the open alleyway, and greater light availability as a result, may explain why edge row trees had a higher number of stems than those in center rows at Empire. Interestingly, the edge effect observed for poplar at Empire was not present for willow at either site, despite the fact that *Salix* spp. are also considered shade intolerant, primary successional species (Argus, 1986).

In contrast to those at Empire, poplar trees in edge rows at Granada did not have more stems than those center rows. However, average basal area per tree at Granada was greater in center rows than edge rows, when averaged across SRWC. If competition for light is a determining factor in the number of poplar stems or per plant basal area, these unique edge effects at each site may be attributable to tree row orientation and resulting differences in light availability. At Empire, the tree rows were planted in a North-South orientation, whereas an approximate Northeast-Southwest (replicates 1 and 2) and East-West orientations (replicate 3) were used to accommodate site features at Granada. In general, East-West oriented alleys (and tree rows) favor alley crop production, especially in northern temperate latitudes (Mutsaers, 1980; Nygren & Jiménez, 1993). However, there is not agreement on what, if any, row orientation results in better tree growth. For loblolly pine plantations in the Southeast United States, no distinction in tree height and basal area 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). In orchard settings, North-South rows have been found to favor increased fruit growth and yield relative to East-West rows (Christensen, 1979), possibly indicative of greater light availability in this configuration.

Short rotation woody crops are typically grown in large block plantations where dense plant spacing may render any effects of row orientation non-existent. Therefore, no information exists regarding optimal row orientation for SRWC in plantations, much less in alley cropping systems. Future work in this system could focus on characterizing potential differences in photosynthetically active radiation between edge and center row positions relative to alley orientation to determine if this factor influences the number of poplar stems, basal area, and the amount of biomass produced.

Currently, edge row poplar trees at Empire have more stems, and therefore, basal area, than those in center rows. However, it is unclear how stem number will impact poplar basal area and biomass production over the 4 year rotation length at Empire. Rae et al. (2004) found that stem number, among other traits, was a strong predictor of biomass yield for a coppiced *Populus trichocarpa* x *Populus deltoides* hybrid. However, this study accounted for only the first year of growth. Others have found the number of stems to be less important over a rotation length for poplar hybrids. Volk (2002) found that first year coppice of NM6 poplar resulted in a greater number of stems than non-coppiced trees, resulting in greater basal area in the second growing season. However, this did not result in increased biomass production in coppiced versus non-coppiced trees over a four-year rotation length (Volk, 2002). Similarly, Herve and Ceulemans (1996) and Proe et al. (1999) found that no-coppice management resulted in greater stem volume and biomass production than coppicing over short rotation lengths for a variety of poplar hybrids, regardless of stem number. In contrast to poplar, coppice of short-rotation willow results in increased biomass production relative to no-coppice management (Volk, 2002).

In this research, poplars were managed in a no-coppice system. The differences between poplar stem numbers at Empire likely arose due to site / resource availability factors with respect to proximity to the alley (e.g. light), and were not a result of coppicing like those of Volk (2002). Therefore, it is hypothesized that these differences will persist and result in increased poplar biomass in edge versus center rows at the end of the first four year rotation.

During the first two years following establishment, competition for resources along the tree-crop interface did not affect dry matter production of herbaceous alley crops. However, herbaceous crops containing C_3 species (MIX and AWG) may be better suited to conditions within the alley as tree height growth continues and shading increases. Plants with a C_3 photosynthetic pathway are generally tolerant up to 50% shade; beyond 50% ambient sunlight, they are light saturated and cannot make use of additional photosynthetically active radiation (Kephart & Buxton, 1993). In contrast, species that utilize the C_4 photosynthetic pathway, such as switchgrass and prairie cordgrass, continue photosynthesis up to nearly 100% ambient sunlight, and are generally not shade tolerant as a result. As a result of these physiological characteristics, some C_3 species have been found to yield as well or better in alley cropping systems than in sole-crop stands in full sunlight. For example, Burner (2003) found no difference in dry matter yield between C_3 species orchard grass (*Dactylis glomerata* L.), grown under 50% shade in a loblolly pine alley cropping system, and that grown in open conditions. Similarly, Thevathasan and Gordon (2004) found no difference in grain yields between open grown and poplar alley cropped barley (*Hordeum vulgare* L.). Thus, AWG and MIX treatments may be best adapted to future light conditions in the alley environment due to C_3 species in these treatments. However, many factors will determine the productivity of herbaceous crops within the alley as crops mature and competition for resources increases.

2.5 Summary and conclusions

Basal area of NM6 poplar after two seasons averaged 1,045 and 1,744 mm^2 $tree^{-1}$ at two sites, while that of Fish Creek willow averaged 770 and 1,609 mm^2 $tree^{-1}$. Edge effects at Empire resulted in greater stem numbers in edge row compared to center row NM6 poplar trees. As a result, basal area $tree^{-1}$ at Empire was greater in edge rows than in center rows, when averaged across species. Conversely, at Granada basal area $tree^{-1}$ was greater in center rows compared to edge rows, though this effect was not present when planting density was taken into account in basal area ha^{-1} analysis. Inconsistency in edge row effects may be a result of variation in light availability at the tree-crop interface due to differences in alley orientation between sites.

Prairie cordgrass and a native polyculture had excellent establishment characteristics (germination and emergence, seedling density, crop/weed composition, and ground cover) and were among the most productive herbaceous crops at both sites, averaging between 7.1 and 11.9 Mt ha^{-1} by the second growing season. During the first two years following establishment, competition for resources did not reduce establishment success or productivity of herbaceous crops along the tree-crop interface.

These results suggest that hybrid poplar and willow and certain herbaceous bioenergy crops may be well suited to alley cropping on riparian sites. Furthermore, these systems may be a viable alternative to annual cropping systems in ecologically sensitive riparian areas in the North Central Region, especially if ecological services such as provision of wildlife habitat, C sequestration, or water quality are of value to landowner or society. However, more research is needed to evaluate crop persistence and productivity within the alley cropping environment over multiple harvest rotations.

3. SURFACE RUNOFF AND TOTAL SUSPENDED SOLIDS LOSSES AS INFLUENCED BY ANNUAL AND PERENNIAL CROPPING SYSTEMS

3.1 Introduction

Cover crops, living mulches, perennial crops, and no-till management have all been proposed as practices that can reduce surface runoff and sediment discharge from agricultural lands in the North Central Region of the United States. Non-point source (NPS) pollution from agriculture has degraded water quality in much of America's farm belt. Surface runoff from agricultural fields can cause significant losses of sediment, particle bound P, and other pollutants to surface waters (Ginting et al., 1998a, b), resulting in turbidity, eutrophication, reduced aquatic habitat quality, and reduced aesthetic and recreational values for lakes and rivers.

In Minnesota, agricultural nonpoint source pollution in the Minnesota River Basin (MRB) has received much recent press and is an issue of increasing public concern. The 303(d) List of Impaired Waters currently contains over 100 water quality impairments for turbidity in the MRB (MPCA, 2011), accounting for up to 90% of the annual downstream loading of 900,000 Mt of sediment in Lake Pepin and the upper Mississippi River (Engstrom et al., 2009; Kelley & Nater, 2000; James et al., 1997; Mulla & Sekely, 2009). Moreover, sediment deposition rates have increased by an order of magnitude since European settlement, with the majority of this increase occurring between 1940 and 1970 (Engstrom et al., 2009), a fact that strongly implicates modern agriculture as a contributing factor. While up to 40% of this sediment can be attributed to bluff and stream bank erosion (Sekely et al., 2002), surface soil erosion rates in upland areas have increased many times since the development of agriculture in the MRB (Mulla & Sekely, 2009).

Over 90% of the 17,000 square mile MRB is dedicated to agricultural land uses, with annual row crops, corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.), covering approximately 65% of the total area (MPCA, 2009). Biannually across this vast area, soybeans provide very little residue cover following harvest, over winter, and into the spring, leaving soils susceptible to erosive forces. In alternate years, corn produces sufficient residue ground cover to reduce soil losses to tolerable levels if residues are left in the field following grain harvest (Lindstrom, 1986; Wendt & Burwell, 1985). Research has shown that retention of crop residue on the soil surface can delay the time to runoff and decrease runoff and soil erosion (Baker & Laflen, 1982).

In annual cropping systems, the extent that crop residue is retained on the soil surface is highly dependent on tillage practices. No-till management retains more residue cover than conventional tillage practices such as moldboard plowing (Triplett et al., 1968), as does the more recent practice of fall chisel plowing (Thoma et al., 2005). In addition to tillage management, integrating cover crops, living mulches, and perennial species for forage or bioenergy feedstock production also present opportunities for increasing ground cover and reducing surface runoff and sediment discharge. These practices provide soil protection by intercepting falling rain and reducing the impact energy of rain drops, improving water infiltration (Folorunso et al., 1992; Manns et al., 2007), and providing considerable water storage capacity in plant residues (Brye et al., 2000). In addition, these practices can provide other high value products and services such as nutrient scavenging and retention (DuPont et al. 2009), wildlife and pollinator habitat (Fargione, 1999), carbon sequestration (McLaughlin & Walsh, 1998), and bioenergy feedstocks for clean energy production.

Extending or increasing annual ground cover in crop fields will reduce the period during which soils are susceptible to erosion and may help to achieve goals for sediment load reduction and water quality improvement in impaired water bodies within the MRB. No-till management, cover crops, living mulches, and perennial crops all offer opportunities to do so. However, a direct comparison of the relative effectiveness of these practices on mitigating surface runoff and sediment losses for the region is not available. Therefore, the objective of this study was to evaluate the effects of perennial crops, living mulches, cover crops, and no-till management on surface runoff and sediment losses from natural rainfall events relative to conventional annual cropping and tillage systems.

3.2 Materials and Methods

3.2.1 Site description

Field studies were conducted from 2007 to 2010 at the University of Minnesota Southern Research and Outreach Center in Waseca, Minnesota (44°03’48” N, 93°32’42” W). Soils at the site are formed in loamy, calcareous glacial till and consist of the Nicollet (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soil series. Slopes at the site are between 3 and 4%, which is characteristic of agricultural fields in the lower Minnesota River Basin. The experimental site has no artificial drainage and was planted with alfalfa (*Medicago sativa* L.) prior to establishment of the experiment.

Seven cropping system treatments, no-till continuous corn (CCN), no-till continuous corn with a winter rye (*Secale cereale* L.) cover crop (CCR), a corn-soybean rotation with conventional tillage (CSC), alfalfa, (ALF), false indigo (*Amorpha fruticosa* L.) with a red fescue (*Festuca rubra* L. ssp. *arenaria* (Osbeck) F. Aresch.) living mulch (IND), short rotation willow (*Salix* sp.) with a red fescue living mulch (WIL), and a warm-season prairie grass mixture (MIX), were established at the experiment site between 2004 to 2006.

Corn hybrid Dekalb DKC 45-82 was planted annually at a density of 81,510 plants ha^{-1} in CCN and CCR plots each year and in CSC plots in 2007 and 2009. Soybean hybrids Pioneer 91Y91 and Asgrow 2107 were planted in CSC plots at 414,960 plants ha^{-1} in 2008 and 2010, respectively. Crop rows were planted parallel to the slope of the field, with average planting dates of 1 May and 15 May for corn and soybean, respectively. Corn treatments were fertilized each year with 168 kg N ha^{-1} as urea, except CSC which was not fertilized during soybean years, 2008 and 2010. Corn was sprayed with a blend of a.i. S-metolachlor (2-chloro-*N*-[2-ethyl-6-methylphenyl]-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide), atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine), and mesotrione (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione) at labeled rates for pre-emergence weed control. All corn and soybean varieties were glyphosate tolerant and were sprayed with a.i. glyphosate (*N*-[phosphonomethyl] glycine) at labeled rates for post emergence weed control.

Corn-soybean (CSC) plots were cultivated once per year in May and tilled in the fall using a chisel plow. No fall tillage was used in CCN and CCR plots. Winter rye was broadcast at 90 kg ha^{-1} into standing corn in the CCR plots in mid September. Each spring, winter rye was killed at anthesis using a roller-crimper, creating a mulch cover into which corn was planted. Grain in all systems was harvested after physiological maturity, October 9 and October 18, on average, in three and four randomly selected 1-m^2 quadrates for soybeans and corn, respectively. Corn stover and soybean straw were left in the field following harvest. Subsamples of grain were taken, dried to a constant weight at 35ºC and used to calculate yields on a DM basis.

In June 2004, a mixture of warm season grasses switchgrass (*Panicum virgatum* L.) and big bluestem (*Andropogon girardii* Vitman) was broadcast seeded at 28 kg ha^{-1} in MIX plots, while alfalfa was broadcast seeded at 14.5 kg ha^{-1} in ALF plots and was incorporated by harrowing. By the start of the experiment in 2007, species composition in MIX plots was about 40% big bluestem and 60% switchgrass. MIX plots were fertilized each year with 56 kg N ha^{-1} as urea and were spot treated with a.i. clopyralid (3,6-Dichloro-2-pyridinecarboxylic acid) as necessary for weed control. No fertilizer or herbicides were applied to ALF plots. Alfalfa was harvested to a 5 cm height at first flower that resulted in 2 cuts in the seeding year and four harvests each year following seeding. Average alfalfa harvest dates over the four years were June 1, July 15, August 14, and September 16. The native grass mixture (MIX) was harvested to a 7 cm-height in late September each year to simulate a biomass harvest regime. For both ALF and MIX, a subsample of herbage was collected at harvest, dried to a constant weight at 35ºC and used to calculate yields on a DM basis.

In June 2006, false indigo (IND) was transplanted at 1.5 m x 1.5 m spacing and under-seeded with 5.6 kg ha^{-1} of creeping red fescue (*Festuca rubra* L. ssp. *arenaria*

[Osbeck] F. Aresch.) as living mulch. In May 2004, willow (WIL) plots were planted with willow cultivar ‘SX64’ (*Salix miyabeana* Seemen) in a “twin row” configuration with 75 cm between rows, 150 cm between double rows and 60 cm between plants within a row for a planting density of approximately 14,332 plants ha^{-1}. False indigo and willow rows were planted parallel to the slope of the field and were spot treated with a.i. glufosinate (2-Amino-4-[hydroxy(methyl) phosphonoyl]butanoic acid) as necessary for weed control. No fertilizer was applied to IND plots, whereas WIL plots were fertilized each year with 112 kg N ha^{-1} as urea. In May 2008 one year following the start of the experiment, WIL plots were under seeded with 5.6 kg ha^{-1} of creeping red fescue. Willow (WIL) and IND treatments were harvested every third and fourth year in 7.0 m^2 and 11.6 m^2 plots, respectively, to simulate a biomass harvest regime. Willow was harvested in fall 2007 and 2010, while IND was harvested only in fall 2010. A subsample of woody biomass was collected at each harvest, dried to a constant weight at 35ºC, and used to calculate yields on a DM basis.

Plant residue and living biomass cover were visually estimated every two weeks in two randomly selected 1 m^2 quadrate in each plot during each growing season throughout the four year study period. Residue and living biomass cover estimates were summed to obtain total ground cover for each two week-period and were used to calculate average monthly and annual cover values for each cropping system treatment.

Each plot measured 4.57 m by 18.29 m, except for IND and WIL plots, which measured 9.14 m by 18.29 m. A furrow was plowed upslope of the plots to ensure that overland flow outside the experiment site would not impact data collection. All plots were hydrologically isolated by a 13 cm high barrier driven approximately 50 cm into the ground at the top and bottom of the plots and 20 cm into the ground on the sides of the plots. The barriers at the bottom of the plots were installed at a 120-degree angle from the sides of the plots to facilitate runoff collection. Reinforced corrosion resistant flumes were installed at outflow points in each plot and a tipping-bucket flow meter system was used to measure and collect runoff water rates and volumes from each runoff unit after a rainfall event. The tipping buckets were equipped with magnetic reed switches and CR10X data loggers (Campbell Scientific, Inc.) that recorded each 1 liter tip. The CR10X logger was programmed to record tip data at 30 minute intervals continuously throughout the season and was powered by a 12 Volt battery with charge maintained by a solar panel.

Runoff volume (L) was determined from tipping-bucket units and was converted to units of liters per hectare (L ha^{-1}). During runoff events, grab samples for analysis of total suspended solids (TSS) were collected in one liter plastic bottles, each perforated with a 2 cm diameter hole in the side. The bottles were positioned so that a 25 ml subsample was collected once with every other discharge from the tipping bucket. Runoff samples were filtered to 0.5 µm; the filtrate was dried, weighed and total solids concentrations (mg L^{-1} and kg L^{-1}) in runoff were calculated. All total solids concentrations were converted to total mass loss units of kg ha^{-1}, which was calculated as the product of runoff volume (L ha^{-1}) and total solids concentration (kg L^{-1}).

Rainfall data were obtained from a standard rain gauge at the experiment site and verified with data from the Southern Research and Outreach Center weather station, which is approximately 2 km from the experiment site. March through November precipitation exceeded the 1971 to 2000 30-year normal by 22%, 25%, 9% and 92% in

2007, 2008, 2009 and 2010, respectively. Spring precipitation over the study period was 11.5% below the 30-year normal, on average, while summer and fall precipitation exceeded the 30-year normal by 64% and 214%, respectively (Figure 3.1). Spring was considered to be March 20 (2008, 2009, and 2010) or March 21 (2007) to June 21 of each year. Summer was considered to be June 22 to September 22 (2008 and 2009) or September 23 (2007 and 2010); and fall was considered to be September 22 or 23 to the date of the last measured liquid precipitation exceeding 12.7 cm (0.5 in) or December 21.

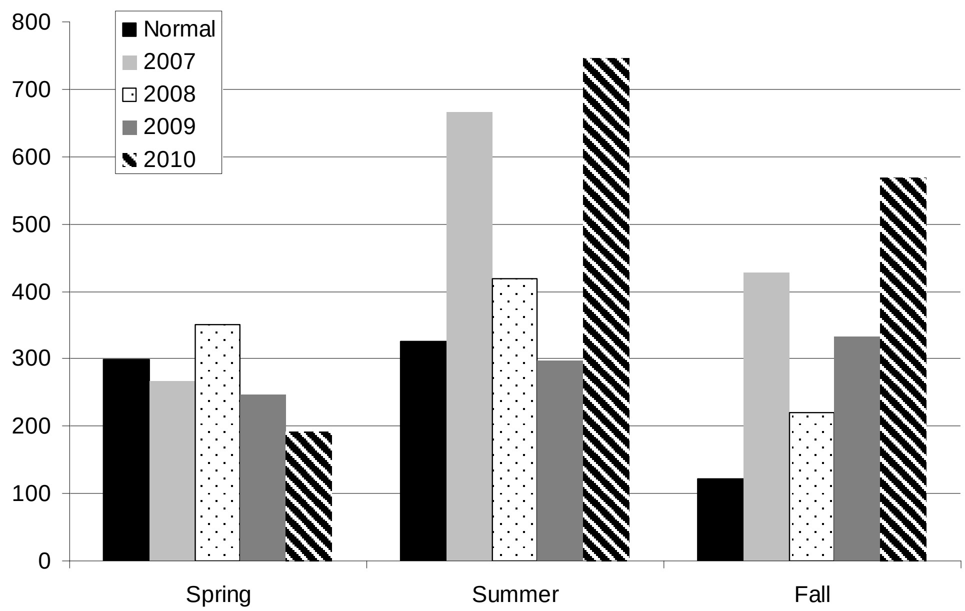

Figure 3.1: Seasonal 30-year (1970 – 2000) precipitation normals and liquid precipitation over the study period at the Waseca Experiment Station in Waseca, MN**.**

3.2.2 Experimental design and statistical analysis

Cropping system treatments were distributed in a randomized complete block design with two replications, for a total of fourteen experimental units (plots). An additional third replicate was used in estimating crop ground cover and yields, but was not instrumented for hydrologic measurements.

Seventy-four rainfall events exceeding 12.7 cm were analyzed for the study period from 2007 to 2010 (Table 3.1), with 28 events occurring in spring, 29 in summer, and 17 in fall. Data for surface runoff and TSS losses were analyzed per rain event to obtain mean event runoff and TSS loss values. Data were also summed to obtain average annual values.

Table 3.1: Summary of rain events greater than 12.7 millimeters at the Southern Research and Outreach Center in Waseca, Minnesota, from 2007 to 2010†.

Period	Number of events	Precipitation				
		Mean	Median	Maximum	Minimum	Total
		mm				
Spring	28	47	32	243	13	1,361
Summer	29	50	31	180	13	1,050
Fall	17	39	32	82	16	620
Overall	74	47	32	243	13	3,031

†A rain event on September 23 - 24, 2010 was omitted due to equipment malfunction during heavy rain.

Event runoff and TSS data were analyzed using repeated measures mixed effects models treating the effects of replicates, cropping system, season, and ground cover as fixed and the effects of year, rainfall event, rainfall amount, and experimental unit as random. Rainfall event (n = 74) was treated as the repeated measure. Annual data were analyzed using analysis of variance (ANOVA). For mixed models, variance components were estimated by REML (Patterson & Thompson, 1971), and approximate likelihood ratio tests using nested null and alternative hypothesis models were performed to verify the significance of components. For all analyses, surface runoff and TSS data were log-transformed to meet assumptions of homoscedasticity of variances and Normality prior to analysis. Results were back-transformed following analysis and are reported as geometric means. Where significant ($p \leq 0.1$) effects were found, Tukey's Honestly Significant Difference (HSD) test for multiple comparisons was used to determine differences between means. Statistical analysis was conducted using R statistical software (R Development Core Team, 2011).

3.3 Results

3.3.1 Ground cover and productivity

Total ground cover did not differ between seasons for perennial cropping systems, whereas CCN ground cover was lowest in spring, CCR lowest in summer, and CSC lowest in fall (Table 3.2). False indigo (IND), WIL, and MIX had among the highest ground cover in each season, while CSC and CCN had lower ground cover than all perennial cropping systems in each season. Ground cover for ALF was lower than other perennial systems in summer due to mid-season harvests, but was still greater than all annual systems. The winter rye cover crop in CCR resulted in increased ground cover in spring and fall relative to CCN.

Willow (WIL) and ALF produced the highest average non-grain biomass yields over the four year study period, 9.6 and 9.4 Mg ha^{-1} yr^{-1}, followed by MIX and IND with 6.5, and 1.1 Mg ha^{-1} yr^{-1}, respectively (Table 3.3). No-till corn (CCN) and CCR produced the highest average grain yields over the four year study with 7.8 and 6.9 Mg ha^{-1} yr^{-1}, followed by CSC with 5.4 Mg ha^{-1} yr^{-1}, respectively. However, if corn and soybean yields are considered separately, CSC had the highest average corn yields with

9.2 Mg ha^{-1} yr^{-1} for years 2007 and 2009, while soybean yields averaged 2.3 Mg ha^{-1} yr^{-1} for years 2008 and 2010.

Table 3.2: Average total ground cover by cropping system and season from 2007 to 2010†

Cropping system	Spring			Summer			Fall		
	%								
False indigo + fescue (IND)	100	a	r‡	100	a	r	100	a	r
Willow + fescue (WIL)	91	abc	r	100	a	r	98	a	r
Native grass mixture (MIX)	94	ab	r	94	a	r	99	a	r
Alfalfa (ALF)	86	bc	r	83	b	r	92	ab	r
Corn-corn, no-till + rye (CCR)	82	c	r	66	c	s	80	b	r
Corn-soy, conv. tillage (CSC)	13	d	t	74	c	r	59	c	s
Corn-corn, no-till (CCN)	17	d	s	67	c	r	60	c	r

†total ground cover is the sum of plant residue and live biomass cover, including living mulches and cover crops where applicable

‡Means in the same column or row followed by the same letter are not significantly different based on Tukey's HSD, alpha = 0.1. The letters a - d are used to compare treatment means within seasons (within columns). The letters r–t are used to compare means of individual treatments between seasons (within rows).

Table 3.3: Biomass dry matter or grain yields§ by cropping system and year.

Cropping system	2007	2008	2009	2010	Annual average
	Mt ha^{-1}				
Corn-soy, conv. tillage (CSC)†	6.7	1.5	10.4	3.1	9.2 (0.4) corn 2.3 (0.1) soy
Corn-corn, no-till (CCN)	7.3	7.3	6.3	10.2	7.8 (0.7)
Corn-corn, no-till + rye (CCR)	7.7	7.4	4.0	8.7	6.9 (0.5)
Alfalfa (ALF)	9.7	8.9	12.3	6.9	9.4 (0.7)
Native grass mixture (MIX)	9.2	5.8	5.8	5.1	6.5 (0.5)
False indigo + fescue (IND)	NH‡	NH	NH	4.6	1.2 (0.1)
Willow + fescue (WIL)	4.9	NH	NH	34.0	9.7 (1.0)

§ Means are reported. For average annual values, means are followed by standard errors in parenthesis. CSC, CCN, and CCR yields reported are for grain only. ALF, MIX, IND, and WIL yields reported are for dry matter (DM)

†For CSC, 2007 and 2009 were corn years, 2008 and 2010 were soybean years.

‡ NH = No harvest

3.3.2 *Surface runoff*

There was a cropping system and season interaction effect on mean event runoff. In the spring, mean event runoff was greater for CSC than CCN, ALF, and MIX (Table 3.4), but no other differences among cropping systems were observed. In summer, mean event runoff was greater for CSC than all other treatments except WIL and IND, and was lower for MIX than all other treatments except CCR and ALF. In fall, mean event runoff was greater for CSC than CCR and MIX, and was greater for CSC, WIL, and IND than ALF.

Table 3.4: Geometric mean event surface runoff by cropping system and season for rain events greater than 12.7 millimeters from 2007 to 2010.

Cropping system	Spring			Summer			Fall		
				Liters ha^{-1}					
Corn-soy, conv. tillage (CSC)	913	a	r†	328	a	s	1,898	a	r
Willow + fescue (WIL)	196	ab	s	157	ab	s	586	ab	r
False indigo + fescue (IND)	120	ab	s	72	abc	s	342	ab	r
Corn-corn, no-till (CCN)	111	b	s	44	bc	t	274	abc	r
Corn-corn, no-till + rye (CCR)	217	ab	r	16	cd	s	160	bc	r
Native grass mixture (MIX)	82	b	r	3	d	s	129	bc	r
Alfalfa (ALF)	38	b	r	14	cd	s	26	c	r

† Means in the same column or row followed by the same letter are not significantly different based on Tukey's HSD (0.1). The letters a - d are used to compare treatment means within seasons (within columns). The letters r–t are used to compare means of individual treatments between seasons (within rows).

Mean event runoff was lowest in summer for all treatments except IND and WIL, for which spring and summer runoff did not differ, but were lower than fall runoff. For CSC, CCR, MIX, and ALF, spring and fall mean event runoff did not differ, whereas for WIL, IND, and CCN spring mean event runoff was less than that of fall. Cropping systems differed in annual surface runoff volume, with CCN having greater runoff than

MIX and IND (Table 3.5). Average annual surface runoff volume did not differ among all other cropping systems due to large within-treatment variation.

Table 3.5: Average annual surface runoff and total suspended solids losses by cropping system for rain events greater than 12.7 millimeters from 2007 to 2010.

Cropping system	Surface runoff ($L\ ha^{-1}$)		TSS ($Kg\ ha^{-1}$)	
Corn-corn, no-till (CCN)	111,723	a[†]	212.6	a
Corn-soy, conv. tillage (CSC)	53,386	ab	60.0	ab
Corn-corn, no-till + rye (CCR)	30,632	ab	10.1	bc
Alfalfa (ALF)	28,434	ab	5.7	bc
Willow + fescue (WIL)	16,412	ab	6.2	bc
Native grass mixture (MIX)	14,850	b	1.8	c
False indigo + fescue (IND)	9,920	b	2.2	c

[†]Means within a column followed by the same letter are not significantly different based on Tukey's HSD (0.1)

3.3.3 Total suspended solids in surface runoff

There was a cropping system and season interaction effect on mean event TSS concentration. In the spring, TSS concentration was greater for CCN than all other treatments except CSC (Figure 3.2). Total suspended solids concentration for MIX was less than for all other treatments except ALF and IND, while those of WIL, CSC, and CCR did not differ. In summer, mean event TSS concentration was greater for CCN, CSC, and WIL than for all other treatments, and was lower for MIX than all other treatments. Those of CCR, ALF and IND did not differ. In fall, losses were lower for ALF, IND, and MIX than all other treatments, while that of CCN was greater than that of CCR. No other differences were observed in the fall.

Mean event TSS concentrations were greatest for all treatments in fall except for IND and MIX, in which spring and fall did not differ, and also ALF in which there were no differences between seasons. Concentrations were lowest in summer for IND and

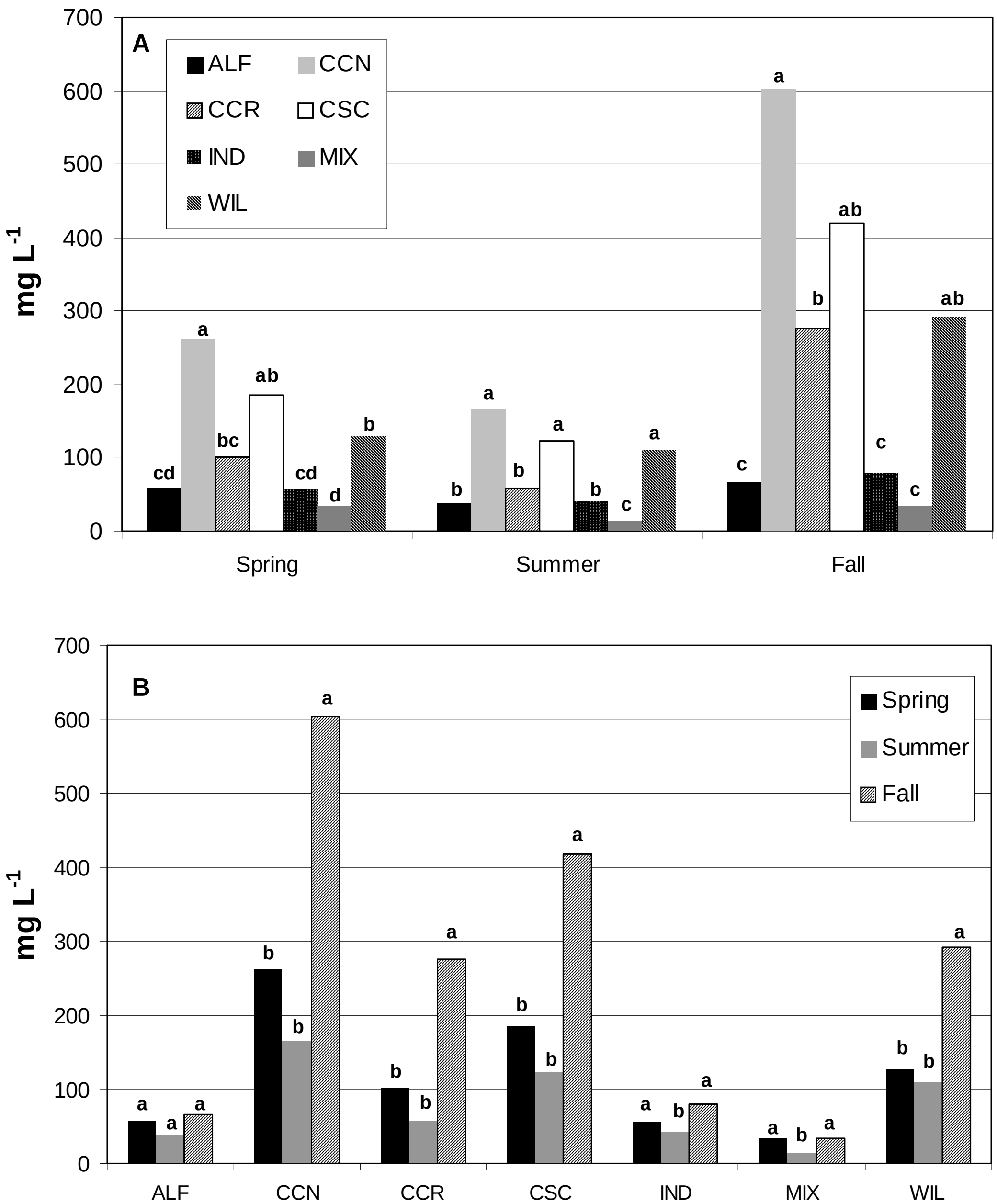

Figure 3.2: Geometric mean event total suspended solids losses for rain events greater than 12.7 millimeters from 2007 to 2010 **A**) between cropping systems within seasons. Within each season, bars with the same letter are not different based on Tukey's HSD, alpha = 0.1 **B**) between seasons within cropping system. Within each cropping system, bars with the same letter are not different based on Tukey's HSD (0.1)

MIX, but no differences were observed between spring and summer for any other treatments. Average annual TSS loss for CCN was greater than all other treatments except CSC (Table 3.5). Average annual TSS losses for IND and MIX were less than those of CCN and CSC, but not different than those of all other cropping systems.

3.4 Discussion

3.4.1 Surface runoff

Despite covariance between total ground cover and mean event surface runoff, there was no correlation between the two variables in the absence of cropping system and seasonal effects. This suggests that cropping system and seasonal influences on surface runoff are defined by factors other than ground cover. Cropping systems can exert significant influence over soil parameters such as aggregate size and stability; pore size and distribution; and infiltration rates, all of which can influence surface runoff (Rachman et al., 2003). Changes in these soil characteristics may have had stronger influence on surface runoff than ground cover, though these characteristics were not measured in this study. In addition, higher than average summer precipitation over the study period, particularly in 2007 and 2010, may have dampened the seasonal effect of ground cover on surface runoff, resulting in greater than average summer runoff and diminishing the effects of high summer ground cover, particularly for annual systems. In addition to possible changes in soil characteristics and higher than average precipitation, the type of ground cover, surface or canopy, may help to explain the unexpected lack of correlation between ground cover and surface runoff. Willow (WIL) had among the highest mean event surface runoff and total ground cover, whereas ALF and MIX also had relatively high total ground cover, but had less surface runoff per rain event than all other treatments except CCR.

This contradiction may be a result of differences in the height of vegetative cover between woody and herbaceous cropping systems. As a result of poor creeping red fescue living mulch establishment in WIL (data not shown), the majority of total ground cover in this cropping system was provided by the willow tree canopy, leaving the soil surface with relatively thin, patchy grass cover. Thus, the majority of ground cover in ALF and MIX cropping systems was closer to the soil surface than that of WIL. Results from IND support this conclusion, as there was better creeping red fescue establishment and ground coverage and lower surface runoff in this treatment than WIL. Furthermore, surface runoff under WIL was strongly influenced by abnormally wet conditions in 2007, which was prior to May 2008 creeping red fescue living mulch establishment. Despite poor creeping red fescue establishment, mean event surface runoff was greater for the period prior to living mulch establishment than for the period after, clearly demonstrating the effect of the living mulch cover on surface runoff.

As expected, mean event runoff for annual systems (CSC, CCN, CCR) was lowest in summer. Total ground cover was highest for CSC and CCN during this period, but for CCR, it was lowest. Mean event runoff for CCR was higher in periods of the most extensive ground cover, spring and fall. Seasonal variations in mean event runoff were also observed for all perennial systems, with those of IND and WIL being highest in fall and those of ALF and MIX higher in spring and fall than summer. Surprisingly, there was no effect of season on total surface runoff (i.e. total runoff did not differ between seasons). Despite lower mean event runoff for most cropping systems in summer, a higher than normal number of summer rain events (and therefore, summer precipitation) over the study period may have resulted in a dampening effect on the expected seasonal variations in total surface runoff.

3.4.2 Total suspended solids in surface runoff

There was no effect of ground cover on mean event or average annual TSS losses. Despite this, the data suggest that cropping systems with greater average annual ground cover had lower annual and mean event TSS losses that those with less ground cover (i.e. perennial and cover cropped annual systems had more ground cover and less TSS loss than conventional annual systems). One exception to this is WIL, which had greater ground cover and mean event TSS losses than CCR. As with surface runoff, relatively high TSS losses under WIL may be due to a predominance of canopy versus surface cover, and also due to the strong influence of abnormally wet conditions in 2007, prior to living mulch establishment. The lack of influence of ground cover suggests that cropping system and seasonal effects on TSS losses extend beyond ground cover to other soil physical and chemical properties.

3.4.3 Further discussion

In many parts of the country, no-till management of annual cropping systems results in less runoff and soil erosion than conventional tillage management. However, on fine textured soils in the upper Midwest, long-term no-till management can result in increased soil bulk density, reduced soil porosity, and ultimately, increased runoff and sediment losses (Lindstrom & Onstad, 1984; Voorhees & Lindstrom, 1983). In this study, no-till management of continuous corn (CCN) resulted in greater per-event TSS losses than a conventionally tilled corn-soybean rotation (CSC), when averaged across seasons. Greater extremes in surface runoff under CCN than CSC suggest that no-till management may have resulted in reduced soil porosity and infiltration capacity relative to conventional tillage. Lindstrom and Onstad (1984) found that no-till management of a Barnes fine loam near Morris, Minnesota, resulted in increased soil bulk density, a reduced volume of macropores, and reduced hydraulic conductivity relative to moldboard and chisel plow tillage. Furthermore, mean event surface runoff was lower and annual runoff and TSS losses higher for CCN than CSC, suggesting that a large proportion of the surface runoff and sediment loss for CCN occurred over a small number of relatively large rain events.

Thus, in this study, conventional tillage resulted in less variable surface runoff and TSS loss response across rain event sizes, whereas the response was much more varied with greater extremes under no-till management. However, the incorporation of a winter rye cover crop in CCR reduced average annual TSS loss by more than 95% relative to CCN. This confirms earlier findings as to the value of cover cropping in no-till systems in the upper Midwest. In agreement with this study, Wendt and Burwell (1985) found that a winter rye or wheat (*Triticum aestivum* L.) cover crop reduced annual soil loss by nearly 96% in a corn for silage cropping system on a silt-loam claypan soil in Missouri.

Annual sediment losses as high as 32,790 kg ha^{-1} y^{-1} have been reported for conventionally tilled corn in small plot studies in the Midwest (Lindstrom, 1986), while more typical losses range from 3,900 to 14,877 kg ha^{-1} y^{-1} (see Burwell & Kramer, 1983; Ginting et al., 1998; Mutchler et al., 1976; Wendt & Burwell, 1985). For no-till corn, losses as high as 5,470 kg ha^{-1} y^{-1} have been reported (Lindstrom, 1986), though are more typically between 600 and 2,500 kg ha^{-1} (see Burwell & Kramer, 1983; Wendt & Burwell, 1985). At 60 and 212.6 kg ha^{-1}, respectively, average annual TSS losses for CSC and CCN in our study were much lower than values reported in the literature for conventional and no-till corn and soybean systems in small plot studies in the region, despite greater than average precipitation over the study period.

Average annual runoff observed in our study was also considerably smaller than previously reported for similar cropping systems in the region. For example, over a 24 year study period, Burwell and Kramer (1983) reported that average annual runoff was 120 mm for conventionally tilled corn on a fine silt loam over claypan soils in Missouri. Average annual runoff of 111,723 and 53,386 L ha^{-1}, with equivalent depths of 11.2 and 5.3 mm for CCN and CSC, respectively, are smaller than even more moderate published values. For example, on a Forman-Buse loam near Morris, Minnesota, Ginting et al. (1998a) found average annual runoff under conventional tillage to be 28 mm. Similarly, Lindstrom (1986) found annual runoff to be 31 and 15 mm (1.22 and 0.59 in) for conventional and no-till systems near Morris, MN. However, values in this study were on par with those reported for conventionally tilled corn in eastern South Dakota, 13 mm (White & Williamson, 1973).

Annual runoff under ALF was 28,434 L ha^{-1} or 2.8 mm equivalent depth, which is similar to the results of White and Williamson (1973) who reported average annual runoff of 3 mm for continuous alfalfa in eastern South Dakota. However, TSS losses for ALF, at 5.7 kg ha^{-1} y^{-1}, were lower than losses found by White and Williamson (1973) of 60 kg ha^{-1} under continuous alfalfa. Average annual TSS loss for MIX, at 1.8 kg ha^{-1} y^{-1}

was on par with results of White and Williamson (1973) in which soil loss from a native tallgrass prairie remnant was below the detection limit for the study. Data for willow and false indigo systems were not found in the published literature, so no direct comparisons were possible. However, surface runoff, runoff ratio and TSS loss values for WIL in this study were comparable to those of conventional annual cropping systems, while those of IND were similar to perennial herbaceous systems ALF and MIX.

Trumann et al. (2001) found that runoff and sediment losses increase by one to two orders of magnitude when slope length increases by the same amount. Thus, plot size can dramatically affect the magnitude of runoff and sediment losses. Slope length in this study was 18.29 m, whereas for similar studies in the North Central Region, reported slope lengths were 22 to 27 m. This discrepancy is not large, and is therefore unlikely to be the sole explanation for lower surface runoff and TSS values in this study than for others in the region. Soil texture, slope, and aspect are other factors that influence runoff and sediment responses, though these factors also did not differ much from those of other published studies in the region.

3.5 Summary and conclusions

Surface runoff and TSS losses were compared for various annual and perennial cropping systems, with and without cover crops, living mulches, and conventional or no-till management. Across seasons, a native grass mixture (MIX) reduced the average sediment concentration in surface runoff by 87% and 90%, while alfalfa reduced concentrations by 74% and 81% relative to a corn-soybean rotation and no-till corn, respectively. Sediment concentrations in surface runoff from short-rotation willow did not differ from the corn-soybean rotation, but were reduced in fall surface runoff by 51% relative to no-till corn. In addition, a winter rye cover crop in no-till corn reduced sediment concentrations by 60% relative to no-till corn with no cover crop, when averaged across seasons. However, sediment discharge in surface runoff from all cropping systems in our study was well below the USDA-NRCS soil loss tolerances of 4.48 – 11.2 Mg ha^{-1} and even below the estimated average mineral soil formation rate of 538 kg ha^{-1} for temperate zones (Alexander 1988).

Variability in surface runoff and TSS loss was due in large part to cropping system treatments. Within cropping systems, variation was due to seasonal effects; likely the seasonal distribution of rainfall and variation in ground cover. However, there were unclear effects of total ground cover on surface runoff, and a lack of effect on TSS losses in this study. Despite this, the results of this research confirm previous findings and assumptions about the relative effects of cover crops, living mulches, and perennial crops on surface runoff and sediment losses in agricultural systems in the North Central Region.

Perennial herbaceous species such as alfalfa or grass mixtures can provide excellent soil and water conservation benefits and sustainable production of forage or bioenergy feedstocks. These crops may be good cropping alternatives to annual systems on potentially erosive or otherwise sensitive soils. False indigo, while providing excellent soil and water conservation benefits with the addition of a living mulch, lacked the productivity necessary to be utilized as a dedicated bioenergy crop. However, no supplemental fertilizer was applied to the false indigo system; all N was provided via biological nitrogen fixation. This low-input system is perhaps better suited for dedicated conservation plantings such as CRP than bioenergy feedstock production. Willow on the other hand, had excellent production characteristics, but provided little benefit in terms of mitigating surface runoff and sediment losses relative to conventionally managed annual systems. The addition of a living mulch improved the conservation benefits of the willow system, but more research is needed to evaluate alternative living mulches or cover crops that can better establish and persist under the shade of the willow canopy.

Finally, in agreement with similar studies, these findings suggest that no-till management with a winter rye cover crop provides superior soil and water conservation to other annual management systems evaluated for the North Central Region. Additionally, crop yields under this regime were competitive with other annual systems, suggesting that on lands that will remain in annual crop production, no-till management of corn with a winter rye cover crop may be a viable cropping alternative.

4. GENERAL CONCLUSIONS

Overall, results suggest that alley cropping with woody and herbaceous perennial bioenergy crops may be a viable alternative to annual cropping systems in ecologically sensitive riparian areas in southern Minnesota. Across both planting sites, the Fish Creek willow or NM6 poplar hybrid and native polyculture or prairie cordgrass alley cropping systems exhibited excellent establishment, growth characteristics, and biomass productivity or basal area, suggesting that these species may be well suited to both the alley crop environment and riparian sites. However, as crops mature competitive interactions along the tree-crop interface may increase. Further evaluation of crop growth dynamics along this interface over time will contribute to a better understanding of the agronomic viability of these alley cropping systems.

It remains to be seen whether production of these alley crops will be sustained at high levels relative to those grown in monoculture on less marginal, upland sites. However, even if yields are reduced as a result of the competitive interactions within the alley system, these systems have many other benefits to offer. Interest in improving water quality, C sequestration, and wildlife habitat in agricultural areas of the North Central Region may provide future incentives for landowners and improve opportunities for adoption of these or similar practices.

In the second experiment, a native grass mixture, alfalfa, and false indigo with a creeping red fescue living mulch reduced average sediment concentrations in surface runoff relative to a corn-soybean rotation and no-till corn. Sediment concentrations in surface runoff from short-rotation willow did not differ from the corn-soybean rotation, but were reduced in fall surface runoff compared to no-till corn. However, sediment concentration in surface runoff from short-rotation willow was reduced following the under seeding of a creeping red fescue living mulch in this treatment in spring 2008. Similarly, a winter rye cover crop reduced sediment concentrations for no-till corn. These results highlight the beneficial effects of living mulches and cover crops in reducing sediment discharge from agricultural lands and confirm previous findings that herbaceous perennials such as native grasses and alfalfa can provide excellent sediment retention relative to annual systems. However, sediment losses for all cropping systems in this study were below the soil loss threshold and estimated soil formation rate for the region.

Perennial herbaceous crops appear to offer the most sustainable approach to bioenergy cropping in terms of soil conservation, though living mulches and cover crops can effectively reduce sediment concentrations in runoff from both woody and annual cropping systems. Alley cropping with both woody and herbaceous perennial bioenergy crops may offer an optimal bioenergy cropping solution by balancing the need for soil conservation with other considerations such as feedstock / landscape diversity and crop productivity.

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Appendix A: Alley cropping study statistical results

Welch two sample t-tests for tree characteristics:

Test	Degrees of freedom	t - value	p - value
Poplar height at Empire = Granada	571.743	6.8056	2.547e-11
Willow height at Empire = Granada	540.405	14.2865	< 2.2e-16
Willow stem no. at Empire = Granada	536.767	19.9687	< 2.2e-16

Analysis of variance table for poplar stem number:

Formula: poplar stems ~ replicate + site + alley position

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
replicate	2	0.28	0.283	0.2757	0.599674
site	1	92.49	92.490	90.2189	< 2.2e-16
alley position	1	10.57	10.565	10.3059	0.001384
residuals	729	747.35	1.025		

Liklihood ratio tests for per plant basal area fixed effects:

Formula: Basal area ~ replicate + clone * site + alley position * site +(1| herb:clone)

Replicate:

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
BSA4	20978	20993	-10486			
BSA3	20972	20992	-10482	8.0689	1	0.004503

Clone:

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
BSA3	20972	20992	-10482			
BSA5	20955	20981	-10472	18.734	1	1.503e-05

Alley position:

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
BSA5	20955	20981	-10472			
BSA8	20947	20978	-10468	9.7408	1	0.001802

Site:

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
BSA8	20947	20978	-10468			
BSA10	20345	20381	-10166	604.03	1	< 2.2e-16

Alley position x site:

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
BSA10	20345	20381	-10166			
BSA11	20332	20374	-10158	14.74	1	0.0001234

Clone x alley position

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
BSA10	20345	20381	-10166			
BSA12	20338	20379	-10161	9.555	1	0.001994

Analysis of variance table for basal area per hectare:

Formula: Basal area ~ replicate + clone * site + alley position * site

Source	Df	Sum Sq	Mean Sq	F val	Pr(>F)
Rep	2	122888280	61444140	8.3231	0.0003464
clone	1	3251014698	3251014698	440.3747	< 2.2e-16
site	1	5340242540	5340242540	723.3765	< 2.2e-16
alley position	1	74246938	74246938	10.0573	0.0017781
clone:site	1	987552856	987552856	133.7716	< 2.2e-16
site:position	1	52974600	52974600	7.1758	0.0080587
Residuals	184	1358358485	7382383		

Analysis of variance table for herbaceous biomass yield:

Formula: Biomass yield ~ Replicate + treatment * site * year

Source	Df	Sum Sq	Mean Sq	F val	Pr(>F)
Rep	2	14.313	7.156	8.6697	0.0002243
Trt	3	59.076	19.692	23.8558	1.000e-13
Site	1	16.958	16.958	20.5432	8.767e-06
year	1	42.852	42.852	51.9127	5.802e-12
Trt:Site	3	29.800	9.933	12.0336	2.035e-07
Trt:year	3	133.356	44.452	53.8508	< 2.2e-16
Site:year	1	43.528	43.528	52.7312	4.093e-12
Trt:Site:year	3	56.604	18.868	22.8575	3.231e-13
Residuals	270	222.875	0.825		

Analysis of variance table for weed biomass in herbaceous crops:

Formula: Weed biomass ~ Replicate + treatment * site * year

Source	Df	Sum Sq	Mean Sq	F val	Pr(>F)
Rep	2	1.052	0.5259	2.2471	0.10768
Trt	3	7.680	2.5601	10.9379	8.400e-07
Site	1	0.026	0.0257	0.1098	0.74064
year	1	1.097	1.0970	4.6868	0.03127
Trt:Site	3	20.810	6.9367	29.6370	< 2.2e-16
Trt:year	3	27.794	9.2646	39.5831	< 2.2e-16
Site:year	1	0.667	0.6669	2.8494	0.09256
Trt:Site:year	3	8.195	2.7315	11.6704	3.251e-07
Residuals	270	63.195	0.2341		

Analysis of variance table for herbaceous crop plant density:

Formula: crop ~ plot + sample + site*treatment + error(sample/plot)

Error: Sample
Source Df Sum Sq Mean Sq
Quad 3 412.28 137.43

Error: Sample:Plot
Source Df Sum Sq Mean Sq F value Pr(>F)
Pt 5 1377.6 275.51 0.5562 0.7318
Residuals 15 7430.4 495.36

Error: Within
Source Df Sum Sq Mean Sq F value Pr(>F)
site 1 2146.8 2146.8 9.7149 0.002309
trt 2 15937.7 7968.8 36.0618 6.962e-13
site:trt 2 1695.8 847.9 3.8372 0.024366
Residuals 115 25412.4 221.0

Analysis of variance table for herbaceous crop weed density

Formula: weeds ~ plot + sample + site*treatment + error(sample/plot)

Error: Sample
Source Df Sum Sq Mean Sq
Sample 3 70.583 23.528

Error: Sample:Plot
Source Df Sum Sq Mean Sq F value Pr(>F)
Plot 5 432.97 86.594 4.075 0.01548
Residuals 15 318.75 21.250

Error: Within
Source Df Sum Sq Mean Sq F value Pr(>F)
site 1 342.25 342.25 19.4602 2.326e-05
trt 2 89.39 44.69 2.5413 0.08318
site:trt 2 136.17 68.08 3.8712 0.02360
Residuals 115 2022.53 17.59

Welch two sample t-tests for herbaceous crops:

Test	**Degrees of freedom**	**t - value**	**p - value**
Prairie cordgrass survival at Empire = Granada	17	2.53	0.0107

Appendix B: Runoff study statistical results

Analysis of Variance Table for average annual runoff

Formula: log(runoff) + block + treatment

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	1	0.112	0.1123	0.0444	0.8339
crp	6	36.101	6.0168	2.3809	0.0429 *
Residuals	48	121.300	2.5271		

Analysis of variance table for average annual TSS

Formula: log(tss) + block + treatment

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	1	0.001	0.0015	0.0003	0.9862778
Treatment	6	170.097	28.3496	5.7889	0.0001353
Residuals	48	235.067	4.8972		

Liklihood ratio tests for mean event runoff fixed effects:

Formula: log(runoff) ~ Rep + trt * season + cover + (1 | YR:Event) + (1 | ppt) + (1 | Unit)

Trt x season

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
rlha3	4783.7	4859.9	-2375.8			
rlha2	4780.0	4913.5	-2362.0	27.659	12	0.006204

Treatment

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
rlha5	4789.0	4836.6	-2384.5			
rlha4	4792.8	4859.5	-2382.4	4.1583	4	0.385

Season

Df	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
rlha4	4792.8	4859.5	-2382.4			
rlha3	4783.7	4859.9	-2375.8	13.14	2	0.001402

Cover

Df	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
rlha6	4792.8	4859.5	-2382.4			
rlha3	4783.7	4859.9	-2375.8	4.42	2	0.035

Correlation analysis between mean event runoff and total grund cover:

$R^2 = -0.09$, $p > 0.1$

Liklihood ratio tests for mean event TSS fixed effects:

Formula: log(TSS) ~ Rep + trt * season + (1 | YR:Event) + (1 | ppt) + (1 | Unit)

Trt x season

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
mgl3	3415.4	3494.5	-1691.7			
mgl2	3417.0	3555.4	-1680.5	22.4	12	0.03328

Season

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
mgl4	3416.1	3485.3	-1694.0			
mgl3	3415.4	3494.5	-1691.7	4.7111	2	0.09484

Trt

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
mgl2	3457.9	3517.2	-1717.0			
mgl1	3417.0	3555.4	-1680.5	72.931	16	3.043e-09

Liklihood ratio tests for mean event runoff ratio (Q/P) fixed effects:

Formula: log(QP) ~ Rep + trt * season + (1 | YR:Event) + (1 | ppt) + (1 | Unit)

Trt X season

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
qp2	4146.3	4225.3	-2057.1			
qp1	4148.2	4286.6	-2046.1	22.06	12	0.03686

Trt

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
qp3	4161.0	4225.2	-2067.5			
qp2	4146.4	4289.8	-2044.2	46.564	16	7.961e-05

Season

	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
qp2a	4152.2	4226.3	-2061.1			
qp2b	4147.8	4231.8	-2056.9	8.3837	2	0.01512

Two sample t-tests for effect of red fescue cover on runoff in willow (assuming unequal variances)

Test	Degrees of freedom	t - value	p - value
Surface runoff in WIL before red fescue cover = surface runoff in WIL after red fescue cover planting	45	2.860	0.00319