Early Season Corn Development in a Kura Clover (*Trifolium ambiguum* Bieb.) Living Mulch

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Michelle Dobbratz

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

John Baker, Julie Grossman

April, 2017

Dedication

In loving memory of Jared.

Carpe diem;

Acknowledgements

Sincere thanks to my advisory committee, Dr. John Baker, Dr. Julie Grossman, and Dr. Scott Wells. Dr. John Baker for encouraging me to explore my varied research interests; providing expert scientific advice, feedback, and ideas; and sharing countless resources. Dr. Julie Grossman for welcoming me into her lab group, encouraging professional development, and sharing important perspectives on research, organization, and methodology. Dr. Scott Wells for sharing his statistics expertise, encouraging me to develop grant writing skills, and helping me think through methodology.

Special thanks to Dr. Gary Gardner for input and equipment enabling my exploration of light quality, Dr. Candice Hirsch for corn seed used in the growth chamber experiment, and Dr. Rex Bernardo for input on the genetic variability of light response in corn. Field support provided by William Breiter, Cody Winker, and the staff at University of Minnesota's Rosemount Research and Outreach Center made this work possible. Thanks to the Departmental staff of Soil, Water and Climate; Horticultural Sciences; and Agronomy & Plant Genetics for administrative support. This project was funded by a Minnesota Department of Agriculture Water Resources grant as part of the Clean Water Land & Legacy Amendment. Thanks to the USDA-ARS for in-kind and technical support.

TABLE OF CONTENTS

List of Tables

List of Figures

1. Literature Review

1.1. Context

Cover cropping, or, the practice of keeping the soil covered with living material outside of the traditional growing season, has long been known to provide a host of agronomic and ecological benefits, however, cover crops are planted on less than 5% of acreage in active production (USDA, 2012). In the Upper Midwest, annual cover crop species have varying degrees of winter hardiness. Winter hardy cover crops provide greater agronomic and ecological benefits, protecting the soil during the rainy spring season. On the other hand, winter hardy cover crops, especially those that are highly productive, can be difficult to terminate in time for the cash crop growing season. US crop insurance policy requires timely termination of cover cropping (NRCS, 2013), further complicating management decision making.

When surveyed, producers in Iowa reported the expense of cover cropping along with the difficulty of establishment and termination as primary obstacles to adoption (Arbuckle and Ferrell, 2012; Dunn et al., 2016). While winter annual species require extra field operations in the fall and spring along with a yearly investment in seeds, perennial species can survive for decades once established. Furthermore, perennial cover crops, also known as perennial living mulches, build on the benefits of traditional winter annual cover cropping by maximizing soil coverage throughout the year. Perennial living mulches cover the field in strips between the cash crop throughout the season, from capturing nutrients during the rainy spring season when fertilizer is applied. Although this system has challenges, with proper management, perennial living mulches are a viable means of protecting soil and water, particularly on highly erodible land (Hartwig and Ammon, 2002).

1.2. Perennial Living Mulches

1.2.1. Overview

Perennial living mulches are permanent cover crops that expand both spatial and temporal coverage of the soil with living material. To minimize competition, broad suppression can be conducted before planting by using sub-lethal herbicide, mowing, or grazing. Inter-row mowing or selective herbicides can be used during the growing season if additional suppression is necessary, but ideally cool-season perennials are selected to complement warm-season annuals. Banded herbicide or strip tillage are often used to prepare cash crop rows while preserving the perennial species. Once established, perennial living mulches are sustained throughout traditional fallow periods and serve as an intercrop during the growing season. This literature review explores what is currently understood about living mulch systems, and outlines possible mechanisms of interference with maize production in strip tilled living mulch systems.

1.2.2. Benefits & Challenges

Perennial living mulches provide a host of agronomic benefits and challenges. The preservation of a perennial species precludes full-width tillage, thereby linking the benefits and challenges of conservation tillage with the suite of benefits and challenges of perennial living mulch. Throughout the year during both the growing season and the traditional fallow season, perennial living mulches have mature roots in place, promoting soil health and intercepting nutrients and chemicals that could be transported into water via runoff or leaching. As a green manure, living mulches can contribute to soil organic matter, which is known to improve water retention and aggregate stability and promote microbial activity.

Multi-species systems reduce pest pressure, achieve greater overall productivity, improve soil structure and fertility, and require fewer inputs than their monocrop counterparts (Malézieux et al., 2009; Kołota and Adamczewska-Sowińska, 2013). When compared with a no cover control, alfalfa and kura clover living mulches increased beneficial insect abundance and predation on European corn borer in a corn-soybean rotation (Prasifka et al., 2006). Leguminous living mulches have also been shown to reduce aphid populations (Costello, 1994). Compared with conventional tillage systems, planting into cover crops, dead or alive, reduces erosion, improves soil bulk density, promotes soil microbial activity, sequesters carbon, and suppresses weeds (Soane et al., 2012). Hall et al. (1984) compared conventional tillage, no-till with corn stover, no-till with a birdsfoot trefoil living mulch, and no-till with a crown vetch living mulch on a 14% slope in Pennsylvania. In their study, living mulches reduced soil erosion to 0.11 Mg ha^{-1}, and in one of three years, crown vetch eliminated erosion entirely. In the no-till with corn stover treatment, erosive losses up to 1.08 Mg ha^{-1} were observed. No-till with corn stover reduced soil loss by 96.7%, but in this study, living mulches offered more complete erosion control for sloped lands than conservation tillage alone.

Perennial living mulches can also interfere with cash crop production by competing for limited resources throughout the growing season and altering cash crop physiology via resource-independent competition such as light signaling. Increased overall productivity brings interspecies competition and fewer agrochemical inputs is accompanied by an increase in overall complexity (Malézieux et al., 2009). In addition to the competitive interactions, the reduced tillage that accompanies perennial living mulch adoption brings additional challenges to corn production, particularly in cool climates. No-till has been associated with a 24% reduction in total maize emergence and delay in emergence of up to a week (Drury et al., 1999). Similarly, no-till systems reduce grain yields by 9-18% (Graven and Carter, 1991; Drury et al., 1999; Afzalinia and Zabihi, 2014). Because of these reported costs, focus is now shifting to moderate tillage practices that can offer the environmental benefits of conservation tillage without significant yield reduction (Pearson et al., 2014; Salem et al., 2015).

Temperature is also a concern, where living mulches have been shown to lower soil temperatures at the 0.1m depth by 0.5-2.8^{o}C compared to monocrop no-till systems (O'Connell and Snyder, 1999; Singer and Pedersen, 2006). A three-year Wisconsin study (Imholte and Carter, 1987) found that no-till corn had reduced total emergence compared to conventional tillage. They found that, at the recommended planting dates, soil at seed depth in the no-till treatment was consistently cooler than the same depth in conventional tillage. Delays in emergence, apparently caused by cool early season soil, led to delayed silking and higher grain moisture content at harvest. Living mulches compete for soil moisture, particularly in the early season, which can lead to slower, less complete corn emergence in dry environments (Eberlein et al., 1992; Hartwig and Ammon, 2002; Duiker and Hartwig, 2004). Conversely, living mulches can conserve soil water, leading to water stress in wet environments (Wiggans et al., 2012b).

1.2.3. Perennial living mulch adoption

In some systems, the challenges of adopting living mulches have been overcome through research and education. Vineyards, typically on steep slopes in regions with abundant precipitation, were early adopters of living mulches as a means of erosion prevention. There were initially cultural obstacles to adoption, including farmer preference for clean rows, the fear of economic loss, and the possibility of increased pest or disease pressure (Hartwig and Ammon, 2002). After several decades of research across Europe, management practices were developed that minimized competition between the living mulch species and the cash crop. This extensive work found no adverse impacts on grape quality, and living mulches often suppress pests, diseases, and weeds (Hartwig and Ammon, 2002). Agronomic benefits have also been attributed to the use of living mulch in agroforestry. Welker and Glenn (1988) found the use of a grass living mulch in an orchard significantly increases aggregate stability, improves infiltration, and lowers bulk density. Although living mulches can compete with perennial fruits for moisture and nutrients in some cases, they are now widely adopted in vineyards and orchards (Kaspar et al., 2005; Hammermeister, 2015).

1.2.4. Living mulches in corn production

In corn production, living mulches were originally explored in the 1950s as a means of building on the water quality and soil health benefits of conservation tillage practices (Zumwinkle, 1995). Early research was conducted by Kurtz, et al. in 1952 in northern Illinois over the course of three years, investigating a variety of leguminous living mulches in grain corn production. Their aim was to identify the mechanism of competition between corn and living mulch. They began by investigating nitrogen and soil water through a factorial design with nitrogen and irrigation additions. In the unirrigated, unfertilized treatment, corn yields in living mulch plots were 9-50% of monocrop corn. By removing water as a limiting resource, unfertilized living mulch plots had corn yields 11- 78% of unfertilized monocrop corn. With adequate nitrogen, rain fed living mulch plots had corn yields 57-84% of monocrop corn, demonstrating nitrogen was a more influential limiting resource in this environment. When supplying abundant irrigation and nitrogen, the corn yield in living mulch plots was 85-94% of monocrop corn. Based on these data, the researchers concluded that competition for nitrogen and water were primary causes of yield loss in living mulch systems.

1.2.5. Living mulch suppression

An alternative to supplying additional resources to the system is to lower the resource demands of the living mulch, benefiting crops by ameliorating resource-independent competition and soil microclimate effects. Prior to cash crop planting, perennial living mulches can be suppressed, either by broadly injuring the living mulch, through selectively terminating strips to prepare a row crop seed bed, or both. Broad suppression can be performed through the application of a sub-lethal dose of herbicide, mowing the living mulch prior to planting the cash crop, or allowing animals to graze on the living mulch for an integrated crop livestock system. Selective termination is most commonly conducted through banded applications of lethal herbicide, however strip tillage is also a viable approach. To further ameliorate competition, living mulches can be additionally suppressed during the cash crop growing season (Duiker and Hartwig, 2004). This approach can offer additional agronomic benefits, such as general weed suppression, and, in the case of leguminous living mulches, nitrogen release. Mechanical suppression can be conducted by mowing between cash crop rows, but chemical suppression is more common, especially since the advent of herbicide resistant corn. Eberlein (1992) found that in an alfalfa-corn system, broad suppression of alfalfa led to higher early season moisture availability. Since early season moisture availability is essential for cash crop germination, emergence, and yield (Kaspar et al., 1990; Jama and Ottman, 1993), the reduction in soil moisture caused by living alfalfa could be impacting maize performance.

1.3. Kura Clover

1.3.1. Species Background

Originating from the Caucasus Mountains near the Kura River, the perennial legume kura clover (*Trifolium ambiguum* M. Bieb) has been studied as a living mulch for corn production. It is naturally adapted to a variety of conditions found in temperate climates. It is naturally found in both highland and lowland areas, and is adapted to tolerate both flooding and drought (Townsend, 1970). Bryant (1974) found that after 40 days of flooding, three varieties of kura clover had over 80% survival. Kura clover responds to drought stress via dormancy, however, even under dry conditions, forage yields of 12 Mg ha^{-1} have been reported, a yield loss of just 9% from irrigated conditions (Stewart and Daly, 1980). Spencer et al. (1975) compared kura clover and white clover productivity, and reported that kura clover thrived through drought stress that almost entirely killed a white clover stand. Kura clover is winter hardy to zone 3, with reports of persistence from the northern U.S. through Canada (Laberge et al., 2005).

Kura clover, also known as Caucasian clover, honey clover, and Pellet’s clover, was introduced to the United States as a forage crop in 1911 (Speer and Allinson, 1985). In the 1940s, the species gained attention from entomologist Frank Pellet, who published a series of articles on kura clover detailing its rhizomatous spreading habit, high nectar quality and anatomical compatibility with honey bees foraging for nectar (Pellett, 1945; Pellet, 1948). Currently, kura clover is most commonly used as a forage crop in temperate regions, where it is valued for its high protein content, palatability, adaptability, and persistence. The protein content of kura clover has been reported to be between 18.3-21.7% (Sheaffer et al., 1992). Outside of Europe, kura clover is resistant to diseases commonly affecting other legume forages, including clover yellow vein virus and clover yellow mosaic virus, which affect other *Trifolium* species (Jones et al., 1981).

Kura clover is slow to establish, but ultimately persistent. In a comparison with alfalfa, red clover, and birdsfoot trefoil conducted in central Minnesota, Cuomo et al. (2003) found that, although kura clover density was initially lower than other species, by the second year after establishment, kura clover stands were denser than any other species. After establishment, it requires little work on the part of the producer as it can survive decades without the need for reseeding (Zemenchik et al., 2000). In forage systems, Wisconsin kura clover researchers report a fertilizer nitrogen replacement value of 93-269 kg ha^{-1} (Albrecht et al., 2003). As an alley crop in agroforestry, kura clover has been shown to significantly supplement nitrogen demands of pecan (Kremer and Kussman, 2011).

Although kura clover has many qualities desirable for forage, honey, and ecosystem services, there remain technical challenges to adoption, most notably agronomic traits, seed production and nodulation potential. Townsend (1970) conducted work exploring kura clover genetics, finding that high variability for agronomic traits (height, vigor, date of flowering, spread, growth habit, and color) and self-incompatibility were identified as areas needing improvement before further development and adoption could take place. Forty years later, few kura clover varieties have been developed, however, selection for agronomic traits in kura clover continues (Riday and Albrecht, 2010). Difficulty of establishment and poor seed availability led to the exploration of vegetative propagation as a strategy for establishing kura clover stands (Baker, 2012). This innovative approach employed a potato harvester and a manure spreader to dig and transplant kura clover crowns, rhizomes, and roots. Vegetative propagation offers a strategy for overcoming kura clover's slow establishment and low seed availability albeit with considerable effort and expense. Lastly, kura clover is not yet suitable for adoption in Europe, due to recent findings that it is susceptible to *Sclerotinia trifoliorum*, contrary to prior reports (Andrzejewska et al., 2014).

1.3.2. Kura Clover as a Living Mulch for Corn Production

Careful selection of living mulch species is essential to the success of the cash crop. For corn, a warm season annual with high nitrogen demands, cool season legumes such as kura clover are ideal. The notable persistence of kura clover also makes it a good choice as a perennial living mulch, but kura clover's most noteworthy characteristic is possibly its rhizomatous structure, enabling it to fill in gaps, outcompete weeds, and develop a tough sod that withstands wheel traffic. As a living mulch, kura clover has been shown to reduce nitrate leaching by 31-74% (Ochsner et al., 2010), runoff by 50%, soil loss by 77%, and phosphorus loss by 80% compared with monocrop corn (Siller et al., 2016).

Kura clover was first investigated for use as a living mulch in corn production in Wisconsin in the late 1990s (Albrecht et al., 2003). Initial work focused on using herbicides for suppression and band killing prior to planting corn (Zemenchik et al., 2000), then moved on to add mid-season suppression in herbicide resistant corn (Affeldt et al., 2004). Mowing and flaming have also been studied as a means of mid-season kura clover suppression (Bard, 2009). Recent work is focusing on tillage for corn row preparation (Pearson et al., 2014). In a recent Colorado study, selective termination of kura clover using an Orthman 1tRIPr strip-till implement improved corn grain yield both years when compared with broad suppression alone (Pearson et al., 2014). The same study found that band killing kura clover with pre-plant herbicide outperformed broad suppression in one of two years.

1.4. Possible mechanisms of interference

Several mechanisms could play a role in grain yield reductions in kura clover living mulch systems. As nitrogen, water, light, and soil temperature are the most important factors in the success of field corn, most researchers point to one of these factors. Understanding interference mechanisms is essential to designing a consistently productive system.

1.4.1. Nitrogen

Although kura clover has excellent nitrogen fixation capacity, as in most legumes it will make use of available soil nitrogen, particularly during establishment (Seguin et al., 2001), possibly competing with corn. It is possible that kura clover recovery from early season suppression could scavenge available nitrogen at the critical V4 stage, when corn typically exhausts kernel reserves and begins relying on soil nitrogen. In a study on nitrate leaching under a kura clover living mulch used for corn production in Wisconsin, Ochsner et al., (2010) detected lower spring nitrate levels under living mulch plots. Similarly, across six farms in Northeast Iowa, Sawyer et al., (2010) observed a reduction in spring soil nitrate levels under kura clover compared with soybean stubble.

Zemenchik et al. (2001) planted corn into a kura clover living mulch that had been either broadly suppressed, band killed in 61cm strips, or completely killed using glyphosate at 1.7, 4, and 3.4 kg a.e. ha^{-1}, respectively. In this factorial design, suppressed and killed kura clover treatments were either unfertilized or sidedressed with 45 kg N ha^{-1}. In the first year, the addition of fertilizer in living kura clover plots had no effect on closing grain yield and population gaps caused by the presence of kura clover. In the second year, however, corn grain yields were 30% lower in fertilized, suppressed kura clover than in unfertilized, killed kura clover. These results suggest that nitrogen competition is not a major contributing factor to corn grain yield loss when grown in a kura clover living mulch. Presumably, suppression of kura clover has the potential to supply nitrogen to subsequent corn, although this has not been definitively documented. Some research suggests economically optimal nitrogen rates (EONR) for corn production in band killed kura are as low as 10-30 kg N ha^{-1} (Berkevich, 2008). Future research on nitrogen cycling in this system should focus on suppression strategies that optimize spatiotemporal nitrogen availability to ensure early season nitrogen demands of corn are being met.

1.4.2. Soil Moisture

Living mulches in corn production systems can promote soil moisture storage in the summer by shading the soil and reducing evaporation (Eberlein et al., 1992; Ochsner et al., 2010). This could mitigate yield loss caused by mid-season drought, as soil moisture at the time of silking is essential for corn yield (Çakir, 2004). On the other hand, although kura clover is less active during the warm season, kura clover living mulch could compete with corn for soil moisture early in the growing season. In one study, kura clover living mulch led to a decrease of 37-50mm in spring soil water (Ochsner et al., 2010). Numerous sources speculate that water is the limiting factor for corn in kura clover living mulch systems, supported by research demonstrating that drought-tolerant corn hybrids do not suffer yield losses when planted in kura clover living mulches (Ziyomo et al., 2013).

1.4.3. Light

Shade avoidance has been observed in corn grown in living mulch systems (Eberlein et al., 1992; Zemenchik et al., 2000). Light signaling is known to be a primary driver for altered early season phenology when corn is grown alongside other plant species (Rajcan and Swanton, 2001; Rajcan et al., 2004; Page et al., 2009). This form of resource-independent competition can alter plant growth, development, and ultimately yield (Ballaré et al., 1990; Liu et al., 2009; Page et al., 2009; Casal, 2012). Green leaves, stems, and petioles attenuate red light and scatter far red light through reflection and transmission, thus altering the ratio of red to far red light that is transmitted through a canopy or reflected laterally. Red light conformationally changes phytochrome into the active form, Pfr, while far red light converts phytochrome into the isomeric form, Pr. Once a plant has adjusted to the environmental light quality, the proportion of total phytochrome in the active form is known as ϕ, phytochrome photoequilibrium, or Pfr/Ptotal. The relationship between ϕ and ζ is asymptotic, with a rapid increase in ϕ occurring in the ζ range between the understory of a dense canopy (ζ= 0.05) and full daylight, (ζ= 1.15) (Smith and Holmes, 1977). This provides a triggering mechanism for shade-avoiding plants to respond to changes in light signals found in the natural environment.

Under plant canopies, light propagated in all directions has been attenuated and scattered, thus ζ in both sun flecks and shade is influenced by shading species and LAI (Smith, 1982). Horizontally propagated light is perceived by vertically oriented tissue, and is a particularly important signal immediately after emergence (Ballaré and Casal, 2000). In corn, shade avoidance in response to depleted ζ results in stem elongation, reduction in biomass, and changes in development (Page et al., 2009). Roots of corn plants in particular suffer from low red:far red light ratios, leaving them at a competitive disadvantage for water and nutrients in the rhizosphere (Rajcan et al., 2004; Afifi and Swanton, 2011).

1.4.4. Soil Temperature

Soil temperature has not been specifically studied in a kura clover living mulch- corn system. There have been observations noting reduced corn performance accompanying lower air temperatures, but they are confounded by the increased competitiveness of kura clover in cool weather (Flynn et al., 2013). Generalizations can be made from what is known about cover cropping and conservation tillage. Cover crops insulate soils, which can benefit crops during hot summer months or stunt crops during cool spring months (Wyngaarden et al., 2015). During wet springs, living mulch systems leave cash crops more susceptible to frost via reduced soil temperature (Martin et al., 1999a).

1.5. Row preparation strategies

A variety of widths have been used for corn row preparation in kura clover living mulch, from 20cm (Berkevich, 2008), to 61cm (Zemenchik et al., 2000). In a three-year Georgia study, a crimson clover living mulch was chemically killed in strips 0cm, 19cm, 45.7cm, 61cm, 72.4cm, and the full 76.2cm wide. Killing strips of crimson clover 45cm or wider led to no reduction in grain corn yield when compared with monocrop corn (Kumwenda et al., 1993). No such research has been done on the optimal width of strip tillage. This thesis will present research on the effect of row preparation strategy on corn production and kura clover health.

2. Rotary Zone Tillage Favorably Affects Corn Growth, Development, and Yield in a Kura Clover Living Mulch System

2.1. Abstract

Kura clover (*Trifolium ambiguum* Bieb.) perennial living mulch has many agronomic and ecological benefits, but corn produced in this system is often lower yielding than monocrop corn, and this yield loss is often preceded by delayed emergence and development. To prepare rows for corn production, kura clover is selectively killed in strips using mechanical or chemical means. We monitored kura clover health, soil moisture & temperature, corn emergence, corn development, and corn yield in four row preparation strategies: herbicide band kill (BK), shank tillage (ST), novel rotary zone tillage (RZT), and dual tillage (DT) which consisted of shank tillage followed by rotary zone tillage. Our primary objective was to compare novel RZT with the traditional strip tillage unit (ST). In 2015, corn grown in RZT plots emerged and developed faster than corn grown in ST plots, but this did not lead to a difference in grain or stover yield. In 2016, corn grown in RZT and DT plots emerged and developed faster than corn grown in ST and BK plots, and grain yield in 2016 was higher (*P*=0.05) in the RZT and DT (10.9 Mg ha^{-1} and 11.6 Mg ha^{-1}) than in the ST and BK treatments (6.9 Mg ha^{-1} for both treatments). Kura clover biomass was not affected by treatment in either year. Based on these results, rotary zone tillage is a promising row preparation strategy in kura clover living mulch for corn production with minimal herbicide use.

2.2. INTRODUCTION

Grain corn production is critical to the economy in Minnesota, generating $5b in 2015 (USDA/NASS, 2015). Minnesota is also home to over 14,000 lakes, the headwaters of the Mississippi, and a $4b yr^{-1} water recreation industry (Kelly, 2012). It is a formidable challenge for row crop production to continue without negatively affecting water quality based ecosystem services, both locally and on a continental scale. In Minnesota, 27% of monitored streams and 10% of private wells have nitrate levels above 10mg L^{-1}, the drinking water standard set to prevent methemoglobinemia, a condition that can be fatal in infants (Minnesota Pollution Control Agency, 2013; Minnesota Department of Health, 2015). Over 70% of total nitrogen in Minnesota surface waters originates from cropland, impacting local aquatic life, threatening human health, and eventually contributing to the hypoxic dead zone in the Gulf of Mexico, an area the size of New Jersey with oxygen levels frequently below that which can support aquatic life (CERN, 2000; Minnesota Pollution Control Agency, 2013). Over half of the lakes in Minnesota in agricultural watersheds do not meet swimming standards, due primarily to eutrophication from phosphorus (Minnesota Polution Control Agency, 2015). Conservation agriculture, particularly on vulnerable land, can play an important role in preventing phosphorus from entering Minnesota rivers (Wilson et al., 2014). As states in the Upper Midwest focus on reducing water quality impacts of grain corn production, there is a need for innovative production strategies that maintain profitability while minimizing the export of nutrients, agrochemicals, and soil.

Perennial living mulches are one management option that could play a role in preventing runoff, leaching, and erosion. Living mulches are permanent cover crops that are grown alongside row crops and remain on the landscape during the fallow season. Living mulches have been shown to reduce surface runoff by 86-98%, soil erosion by 98-99% (Hall et al., 1984b), and nitrate leaching by 86% (Liedgens et al., 2004) when compared with conventional practices. Living mulches can positively impact soil health indicators, increasing microbial biomass (Alvarez and Steinbach, 2009), organic matter content (Duda et al., 2003), and aggregate stability (Raimbault and Vyn, 1991). Living mulches provide benefits such as weed suppression (Teasdale, 1996), pest and disease regulation (Ramert, 1996; Ntahimpera et al., 1998), and increased water infiltration (Singh et al., 2009). Leguminous living mulches also have the capacity to fix nitrogen, which can reduce the fertilization requirements of the row crop (Hall et al., 1984b; Grubinger and Minotti, 1990; Duiker and Hartwig, 2004). With grain corn on 90 million acres in the U.S. (USDA Economic Research Service, 2016), living mulches have the potential to impact the landscape if applied to even a small portion of corn production.

However, for corn producers to capitalize on these benefits, economically feasible management strategies must be developed that mitigate the risks and costs of adopting this system. Management of perennial living mulch systems necessitates zonal preservation of the living mulch, precluding the use of full width tillage. Thus, living cover systems share some challenges commonly associated with conservation tillage practices, such as no-till and strip-till. Living mulches can reduce cash crop germination rates, delay emergence and development, and leave cash crop seedlings at a higher risk of damage in the case of late frost (Martin et al., 1999b). No-till systems have been shown to lower soil temperatures by 1.0-1.8°C compared to conventional tillage, a likely mechanism in delayed corn emergence (Cox et al., 1990), and living mulches can further lower soil temperatures by 0.5-2.8°C compared to monocrop no-till (O’Connell and Snyder, 1999; Singer and Pedersen, 2006). Seedbed temperatures are an important factor in corn emergence rates (Cutforth et al., 1985; Schneider and Gupta, 1985), and yield penalties from delayed emergence can be substantial; Rutto et al. (2014) observed that for each day corn emergence was delayed, grain yields were reduced by 122 kg ha^{-1}.

A variety of strategies exist to reduce the interference from living mulches while maintaining their perenniality. These strategies focus on either suppressing the living mulch through broad suppression, or selectively killing the living mulch in rows, and are often used in combination. Before planting the cash crop, living mulches can be suppressed through mowing, grazing, or sub-lethal herbicide. Cash crop seedbeds can be prepared in the spring through some form of partial width or with banded herbicide. During the growing season, living mulches can be further suppressed by mowing before the cash crop gets too high, or by applying a selective herbicide.

Kura clover (*Trifolium ambiguum)*, a perennial forage legume, has potential as a living mulch without significantly disadvantaging corn yield if properly managed (Zemenchik et al., 2000; Affeldt et al., 2004; Pearson et al., 2014). However, most effective strategies rely on high doses of band-applied herbicide that could potentially affect the health and long-term survivability of the clover, and popular herbicide regimes are not consistently successful at adequately suppressing kura clover (Affeldt et al., 2004). We propose that more aggressive zone tillage prior to planting might be a viable alternative to band herbicide applications, providing for more thorough control of kura clover and higher corn yields. This experiment was conducted to evaluate the effects of varying zone tillage intensity in kura clover living mulch for grain corn production, and to compare the effects of tillage in general with herbicide band kill. We hypothesize that more aggressive zone tillage will 1) promote early season corn development, 2) improve overall corn yields, 3) promote corn seedbed warming, and 4) improve soil moisture availability. Further, we expect that zone tillage will maintain healthier kura clover living mulch than herbicide band kill.

2.3. MATERIALS AND METHODS

2.3.1. Site and Experimental Design

Field studies were conducted in 2015 and 2016 at the Rosemount Research and Outreach Center (44°43' N, 93°05' W) on a Waukegan silt loam (mesic Typic Hapludoll) with good natural drainage and low erosion potential. The experimental location was within an unirrigated field of 'Endura' kura clover (*Trifolium ambiguum* Bieb.) established in 2006 and used as a living mulch for corn and soybean production since 2008. In 2015, the experiment followed soybean production, while in 2016 the experiment followed kura clover production. Four replications were arranged in a randomized complete block design. Experimental units comprised six 38.7m rows of corn with 76.2cm row spacing.

2.3.2. Agronomic Management

Seedbed preparations were performed 5 May 2015 and 18 May 2016, according to one of the following treatments: 1) band kill herbicide burn down (BK) with 4 kg a.i. ha^{-1} of glyphosate [N-(phosphonomethyl) glycine] with a standard tractor-mounted boom with nozzles set to a 30.5cm spray width, 2) shank-till (ST) using an Orthman 1tRIPr shank-tillage implement with ground-driven wavy coulters (Orthman Manufacturing Inc., Lexington, NE), 3) rotary zone tillage (RZT) using a custom PTO-driven rotary tine implement (Northwest Tillers, Yakima, WA), and 4) Double tillage (DT), in which shank tillage was followed by rotary zone tillage. The double tillage treatment was added to provide maximum soil disturbance for the purposes of evaluating the novel RZT implement. Immediately following seedbed preparation, a corn hybrid with glyphosate resistance (2015- Golden Harvest GO1O52; 2016- Dekalb DKC 45-65) was seeded at 79,000 seeds ha^{-1} with a six-row John Deere 7000 planter (John Deere, Moline, IL). A shorter season hybrid was chosen in the second year due to the later planting date. Kura clover was 10-20 cm tall at the time of planting and was mowed to a height of 5cm prior to corn emergence. Starter fertilizer of 9-18-9 at 56 L ha^{-1} was applied at planting, and in mid-June side dressing of 28% liquid N occurred (145 kg ha^{1} in 2015 and 123 kg ha^{1} in 2016). To control weeds and suppress, but not kill, kura clover, 1.04 a.i. kg ha^{-1} of glyphosate was broadcast on 8 June 2015 and 2 June 2016.

2.3.3. Data Collection and Analysis

Installation of soil sensors occurred within two days of planting. In each plot, two calibrated matric potential and temperature sensors were installed at the 5cm depth in the seed bed. Soil volumetric water content and temperature sensors were placed at the 45cm, 35cm, 25cm, 15cm, and 5cm depths in each treatment to characterize temperature and moisture dynamics within the soil profile. Half hour averages were logged for the entire growing season. Specific instruments used were MPS-6 soil water potential and temperature sensors, and 5TM soil moisture and temperature sensors, logged with Em50 loggers (Decagon Devices, Pullman, WA).

Daily counts of emerged corn plants per 2 m unit of row length were recorded at four locations in each of the seedbed preparation treatment plots. Corn height was recorded weekly as the distance between the soil surface and the arch of the uppermost leaf that had emerged at least 50% (Hager and Sprague, 2002), beginning at emergence and continuing through vegetative maturity. Development was characterized using the leaf collar method (Abendroth et al., 2011) from emergence through the seven-leaf stage (V7). Leaf area index was recorded weekly in 2016 using an AccuPAR LP-80 (Decagon Devices, Pullman, WA) beginning at canopy closure and continuing through tasseling. Corn stover yield was determined by hand sampling 3m of row down to 15cm on 9 October 2015 and 24 October 2016. Grain was harvested mechanically in 2016 with a plot combine and scale on 24 October 2016 and adjusted to 15.5% moisture concentration. In 2015, mechanical harvest was precluded by raccoon damage in a small portion of the field. Hand sampling was conducted by removing cobs from two 3m lengths of row per plot and drying to a consistent weight before adjusting to 15.5% moisture. Kura clover percent cover was visually scored monthly, beginning the week before planting. Biomass of kura clover was periodically assessed in between corn rows by collecting four 0.1 m^2 samples per plot.

Analysis of variance ($P = 0.05$) procedures using the anova() function of R (R Core Team, 2016) were used to test the effects of year, treatment, and treatment by year interactions for all measurements (Appendix- Table 5). Linear models were constructed using the lme function of the nlme package (Pinheiro J., Bates D., DebRoy S., 2016), considering year and treatment fixed effects and blocks as random effects. When significant differences were found ($P < 0.05$), post-hoc analysis was conducted using Tukey’s HSD with Holm’s adjustment to separate means (Mendiburu, 2016). The Holm procedure was chosen because it has higher power than the Bonferroni procedure, without the additional restrictions of other Bonferroni derivatives (Olejnik et al., 2016).

2.4. RESULTS AND DISCUSSION

Both growing seasons had warmer and wetter than average conditions overall (Table 1). In 2015, total rainfall from May to September was 99 mm above the 30-yr long-term average. Monthly precipitation was consistently above average through July, which was the wettest month. August was the only month of 2015 with a rain deficit, receiving 76mm of precipitation. Precipitation in 2016 was overall 33% higher than average. In 2016, the month of May had a deficit of 24 mm, and moisture stressed corn was noted in late June through early July. Surplus rainfall and heat in September 2016 extended the corn growing season and delayed subsequent harvest both seasons. Monthly average temperatures were at or above 30-year averages throughout the duration of the experiment, with September 3 and 2 degrees above average in 2015 and 2016 respectively.

2.4.1. Kura Clover Health

Kura clover biomass production did not vary by treatment at pre-treatment, mid-season, or post-harvest time points in either year (Figure 1). In 2015, kura clover dry matter pre-treatment ranged from 933-1365kg ha^{-1}. In 2016, kura clover dry matter pre-treatment ranged from 1660-1866kg ha^{-1}. There were no differences in 2016 percent cover, but there were differences in percent cover at the post-harvest observation in 2015 (Figure 2). The significant differences in percent cover in 2015 had disappeared by the following year, suggesting the rhizomatous spreading of the kura clover had spread throughout the interrow of the 2015 plots.

2.4.2. Early Season Seedbed Microclimate

There were no significant differences in soil moisture between row preparation treatments in either year (Figure 3; Figure 4; $P = 0.05$). This is contrary to the widespread finding that more intensive tillage lowers soil water availability (Xu and Mermoud, 2001; Alletto et al., 2011; Salem et al., 2015), but in agreement with findings by Schwartz et al. (2010) who found in a stubble mulch system, greater evaporation in tilled plots was offset by greater infiltration in no-till plots. In this case, tillage disturbed kura clover roots, which reduce seed depth soil moisture through both transpiration and percolation (Ochsner et al., 2010). Based on our observations, it is likely seed depth soil moisture depletion via tillage and via kura clover roots were of comparable magnitude.

The average temperature between planting and 50 DAP was affected by treatment in 2016, but not in 2015 (Table 2; $P = 0.05$). In 2016, DT plots were 1.2 and 1.4^{o}C warmer than BK and ST treatments, respectively – comparable to values reported by Licht and Al-Kaisi (2005). Tillage increases early seedbed temperature by removing insulative plant material from the soil surface and lowering the soil albedo, providing for more absorption of solar radiation (Johnson and Lowery, 1985). Burrows and Larson (1962) found that applying mulch at a rate of 2.25 Mg ha^{-1} lowered soil temperature at 10cm by 0.4^{o}C. In 2015, there was 1.2 Mg ha^{-1} kura clover biomass at the time of row suppression, which did not perceptibly insulate the soil. While tillage can impact soil temperature by lowering the albedo, soil moisture is a stronger factor in albedo than surface roughness (Oguntunde et al., 2006). It is possible that the abundant soil moisture near the surface superseded any effects tillage might have had on albedo.

2.4.3. Corn Emergence and Early Season Development

Compared to ST, both RZT and DT increased the rate of corn emergence in both years (Figure 5, $P = 0.05$). In 2015, corn in RZT, BK, and DT plots reached 95% emergence one day faster than corn in ST plots. In 2016, corn in RZT and DT plots reached 95% emergence three days faster than corn in BK and ST plots. Since corn emergence is largely a function of soil temperature (Cutforth et al., 1985; Schneider and Gupta, 1985), the increased seed depth soil temperature in the RZT and DT plots in 2016 was likely responsible for faster corn emergence. Previous work on kura clover living mulch for corn production has found that in years when the kura clover is highly productive, glyphosate alone may not fully terminate kura clover (Affeldt et al., 2004). Given that kura clover was 50% more productive in 2016 than 2015, it is likely that the BK treatment was more effective in 2015 than 2016, providing for better conditions for corn emergence.

Treatment effects on early season vegetative development echoed treatment effects on corn emergence. Compared to ST, both RZT and DT increased the rate of corn early season vegetative development in both years (Figure 6, $P = 0.05$). In 2015, the difference in corn development was most pronounced at 42 DAP, when the mean vegetative stage of corn in RZT, DT, and BK treatments was 0.5-0.7 higher than the mean vegetative stage of corn in the ST treatment. In 2016, the difference in corn development was most pronounced at 36 DAP, when the mean vegetative stage of corn in RZT and DT treatments was 0.7-1.8 higher than the mean vegetative stage of corn in the BK and ST treatments.

2.4.4. Corn Grain and Stover Yield

In 2015, neither grain yields nor stover yields varied by treatment (Table 3). Grain yields in 2015 averaged 13.8Mg ha^{-1} and stover yields averaged 8.3Mg ha^{-1}. In 2016, corn grown in DT and RZT treatments produced 4.0 - 4.7Mg ha^{-1} more grain than corn grown in ST and BK treatments, and corn grown in DT plots produced 5.0Mg ha^{-1} more stover than corn grown in ST plots. Both years were considered favorable corn production years in southern MN, and no pests or diseases were observed in either year. However, slight leaf curling was observed in corn around the V6 stage in 2016. Cox et al., (1990) found that reduced tillage only impacted ultimate corn yields in seasons with some degree of moisture stress. This is in accordance with our findings that more intensive rotary zone tillage had no effect on corn yields in a consistently wet year, but positively affected corn yield when mid-season moisture was limiting.

2.5. CONCLUSION

Our results indicate that rotary zone tillage (RZT) is a promising strategy for suppressing kura clover living mulch in corn systems in the Upper Midwest without adversely affecting the health of the kura clover. Living mulch management requires careful attention, particularly during the critical early season. During this critical period, corn grown in seedbeds prepared using double tillage (DT) and RZT were consistently ahead of corn grown in seedbeds prepared using shank tillage (ST) alone. RZT led to higher grain yields than ST in 2016, likely due to warmer early season seedbed temperatures. Given the comparatively warmer seedbeds in RZT plots in 2016, it is likely the additional kura clover biomass exacerbated the negative effects of minimum tillage, delaying emergence and development of corn grown in ST plots. Further research across multiple environments and years is needed to assess the consistency of rotary zone tillage. To determine best management practices in this system, future research should focus on understanding soil water balance and temperature under rotary zone tillage with varying initial kura clover vigor for specific soil textures and climatological conditions.

2.6. Figures

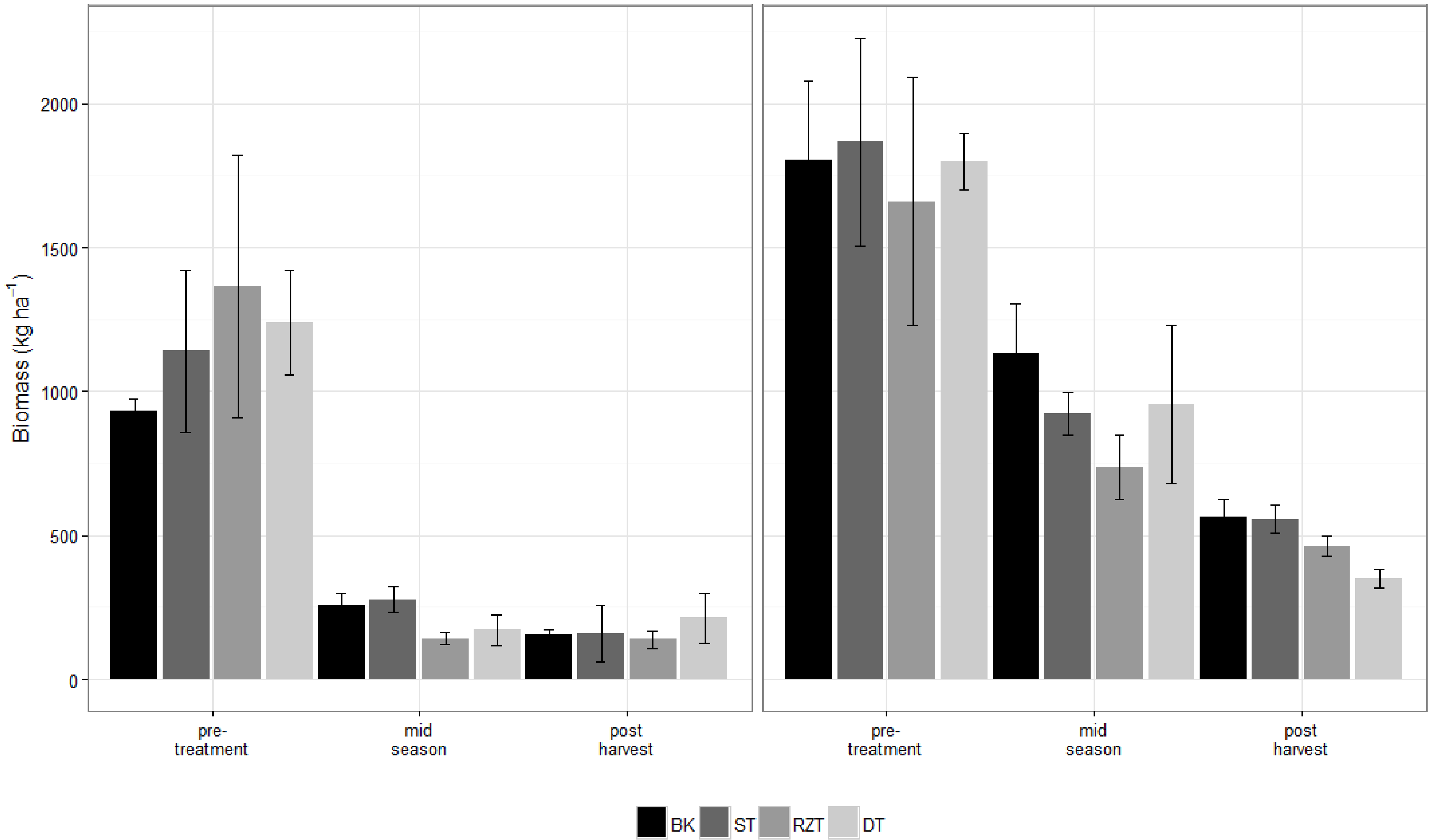

Figure 1 -- Kura clover biomass by treatment throughout the growing season (kg ha^{-1}).
BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatments. Error bars represent standard error of the mean.

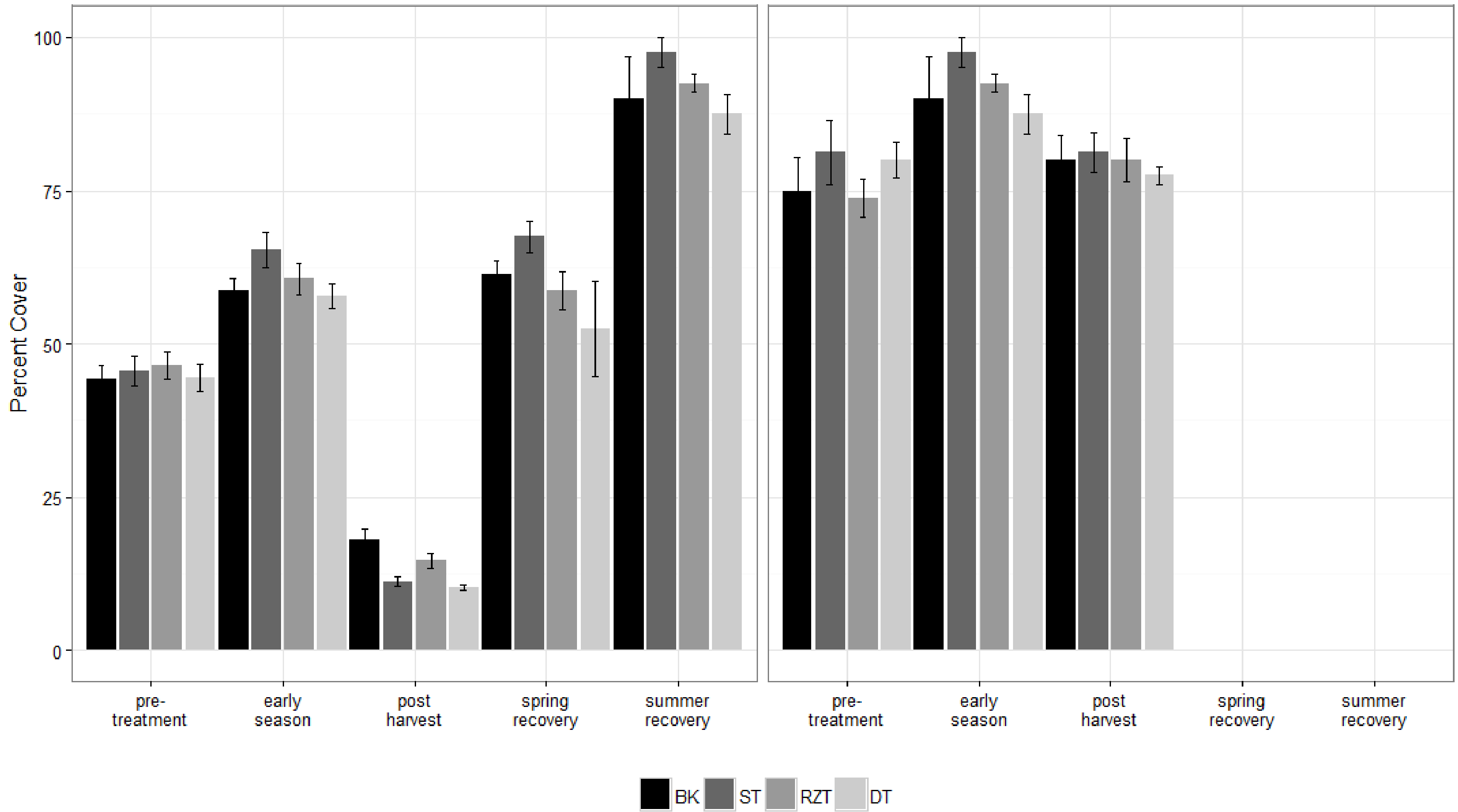

Figure 2 -- Percent kura clover cover by treatment throughout the growing season. Spring and summer recovery shown for 2015 plots only.
BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatments. Error bars represent standard error of the mean.

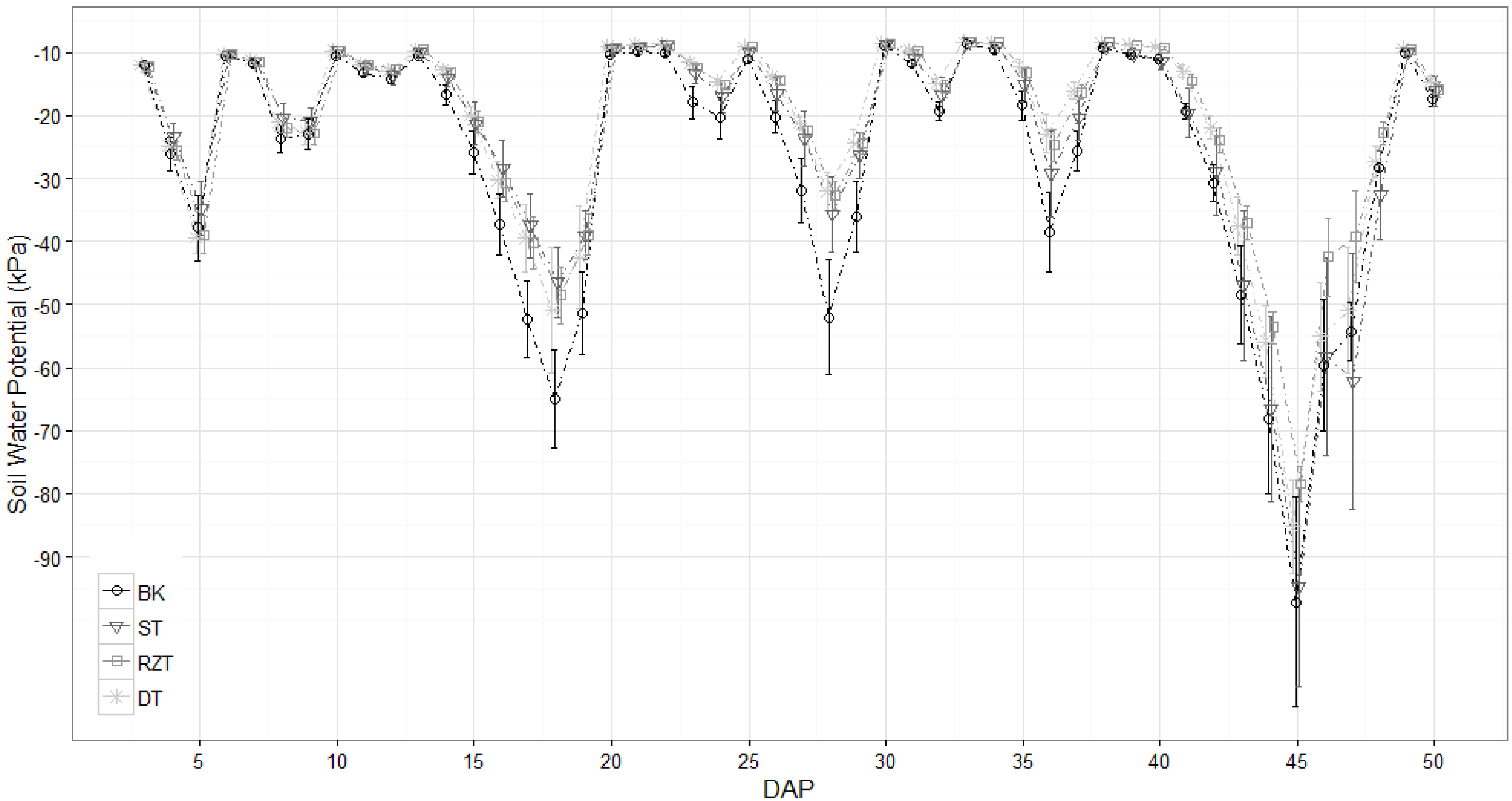

Figure 3. Daily precipitation events (top) and soil water potential by treatment (bottom) between 3 days after planting and the six-leaf stage of corn at Rosemount, MN (2015). Precipitation data obtained from Minneapolis/ St. Paul Airport Station Global Historical Climatology Network data obtained from the Midwestern Regional Climate Center.
BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatments. Error bars represent standard error of the mean.

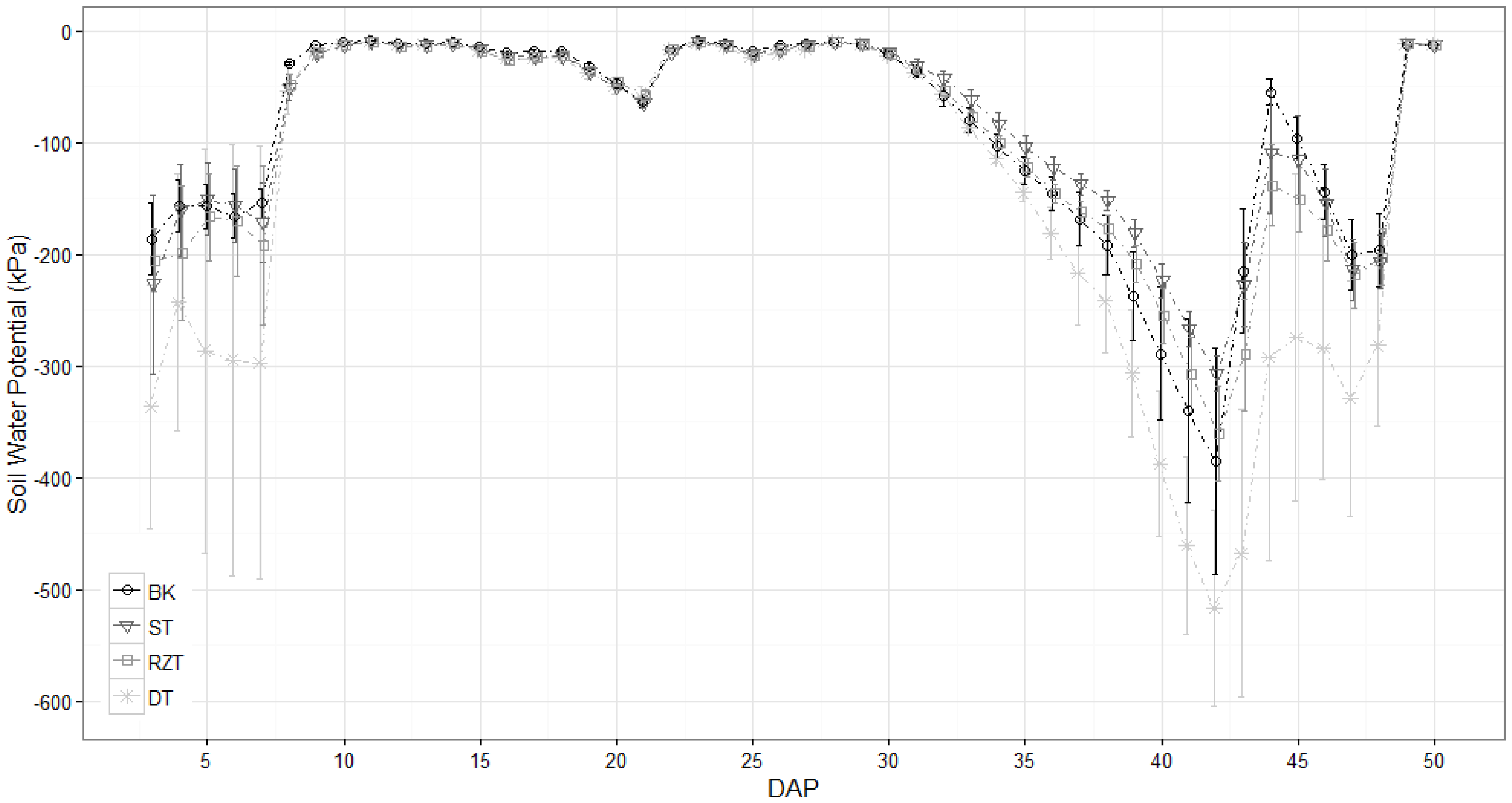

Figure 4. Daily precipitation events (top) and soil water potential by treatment (bottom) between 3 days after planting and the six-leaf stage of corn at Rosemount, MN (2016). Precipitation data obtained from Minneapolis St. Paul Airport Station Global Historical Climatology Network data obtained from the Midwestern Regional Climate Center.
BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatments. Error bars represent standard error of the mean

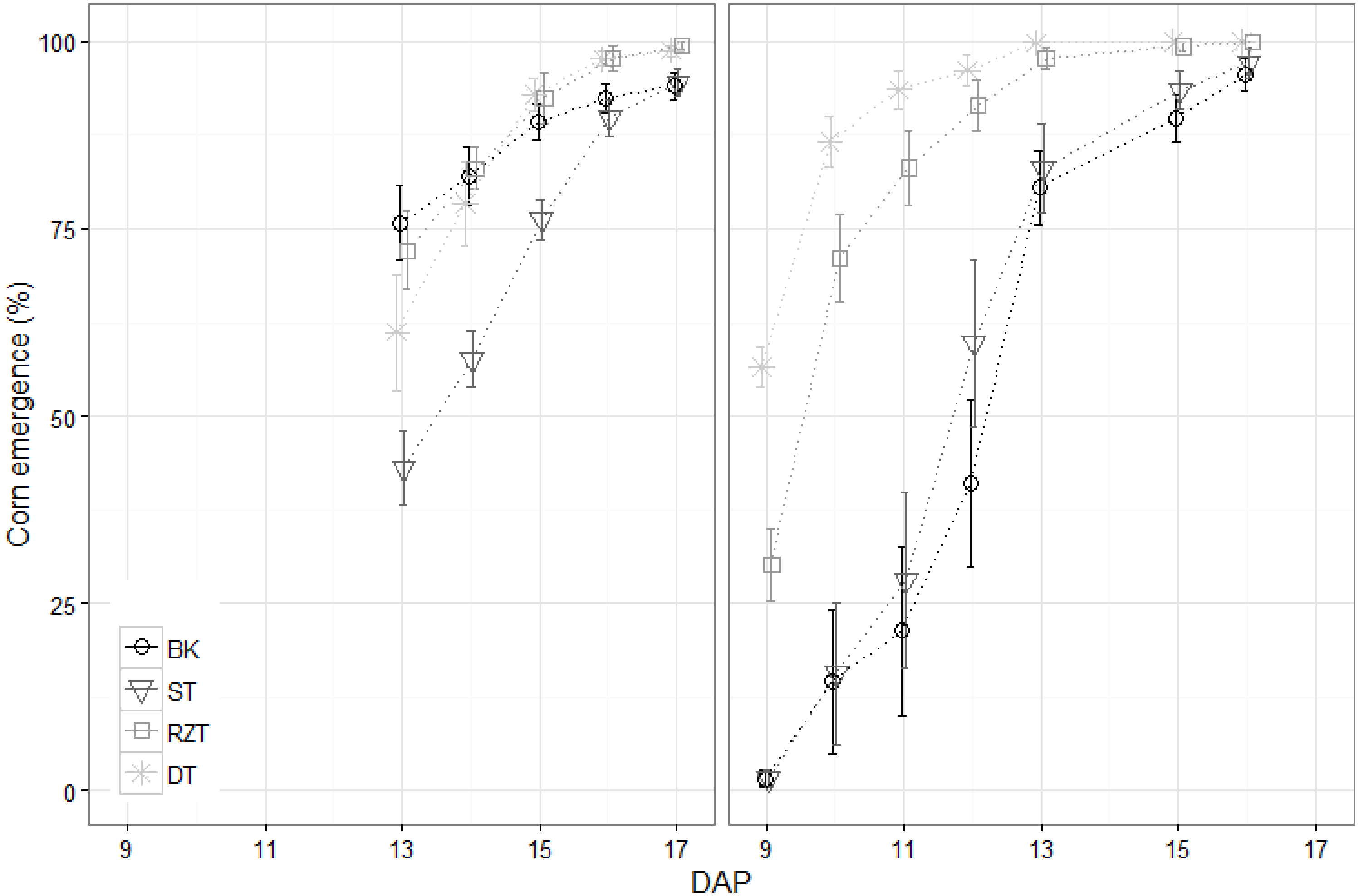

Figure 5. Corn emergence as percentage of target population by treatment in 2015 (left) and 2016 (right).
BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatments. Error bars represent standard error of the mean.

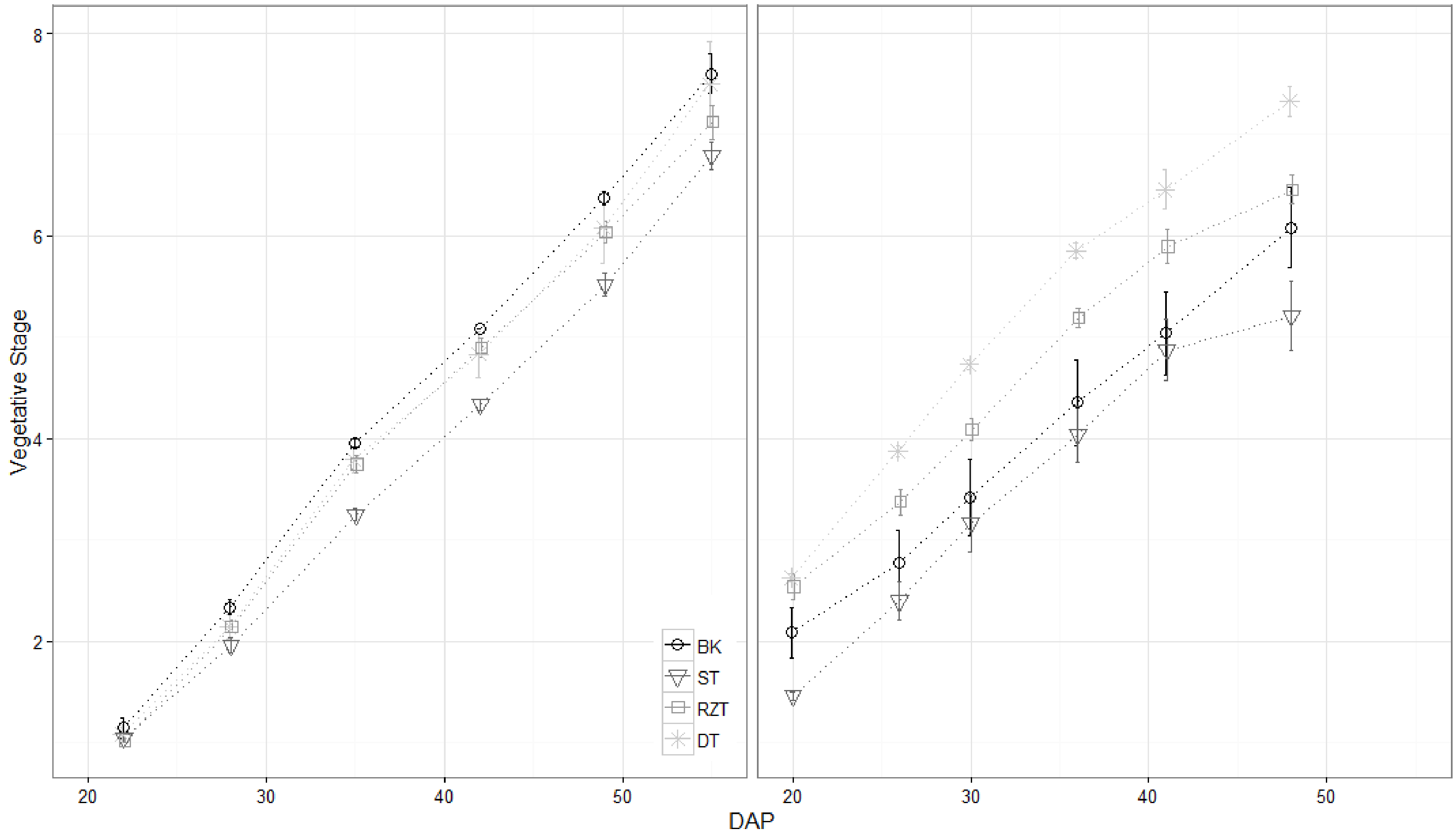

Figure 6 -- Vegetative stage (collars visible) of corn by row preparation treatment in 2015 (left) and 2016 (right). BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatments. Error bars represent standard error of the mean.

2.7. Tables

Table 1- Monthly precipitation and mean monthly temperatures for Rosemount, Minnesota. Minneapolis/ St. Paul Airport Global Historical Climatology Network data obtained from the Midwestern Regional Climate Center.

Month	Normal‡	2015	2016
Total monthly precipitation, mm			
May	85	90	61
June	108	112	114
Jul.	103	186	129
Aug.	109	76	199
Sept.	78	118	139
Sum	483	582	642
Average monthly temperature, °C			
May	15	15	16
June	20	21	22
Jul.	23	23	24
Aug.	22	22	23
Sept.	17	20	19

‡ Normal precipitation and temperature are based on 30-yr means.

Table 2- Average soil temperature in seedbed (5cm depth) through 50 days after planting across treatments with standard error.

	2015		**2016**	
Trt	Temp (ºC)	SE	Temp (ºC)	SE
BK	17.2	0.24	19.9	0.59
ST	16.9	0.29	19.7	0.30
RZT	17.2	0.25	20.5	0.22
DT	17.1	0.36	21.1	0.20

BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatments.

Table 3- Yield of corn stover and grain by row preparation treatments in Rosemount, MN.

Trt	Grain yield†	Stover yield§	Grain yield†	Stover yield§
	2015		2016	
		Mg ha^{-1}		
BK	14.2	8.6	6.9 b»	5.3 ab
ST	13.2	7.5	6.9 b	4.8 b
RZT	13.7	8.7	10.9 a	8.3 ab
DT	14.1	8.4	11.6 a	8.8 a

†Corn grain yields are adjusted to moisture content of 155 g kg^{-1}

§Stover yields are reported on a dry matter basis.

»Within columns, numbers associated with different letters are different at $P = 0.05$ per Tukey's HSD.

BK = band kill, ST = shank tillage, RZT = rotary zone tillage, and DT = double tillage row preparation treatment.

This page intentionally left blank for sectioning purposes.

3. Shade avoidance in early season corn is influenced by proximity to living mulch

3.1. Introduction

Some plants subjected to the lower red:far red light ratio characteristic of light reflected off plant matter will exhibit physiological symptoms of shade avoidance (Ballaré et al., 1990). In shade avoiding species, the photoreceptor phytochrome responds to this proportion of red light (centered at 660nm) and far red light (centered at 730nm), a light quality indicator referred to as ζ or R:FR. As distance from neighboring plant canopies increases, ζ increases asymptotically (Smith et al., 1990). Shade avoidance syndrome are triggered by low ζ, even when photosynthetically active radiation (PAR) is not limiting (Holmes and Smith, 1975; Morgan and Smith, 1979). To compete with neighbors for access to PAR, plants alter their growth and development, preferentially investing in above-ground tissue, elongating stems and leaves and accelerating the onset of reproduction. This signal effect is spatially localized but temporally persistent- individual leaves exposed to low ζ will increase sucrose export and senesce, but effects can persist after light quality returns to that of unfiltered daylight (Ballaré & Casal, 2000).

Corn seedlings are sensitive to light quality signals, and early life neighbor detection can alter development, reduce stress tolerance, and adversely impact reproduction and yield. The most consistently observed response to lower ζ in shade-avoiding species is hypocotyl elongation, often at the expense of root development (Demotes-Mainard et al., 2016; Montgomery, 2016; Roig-Villanova and Martínez-García, 2016). Stem elongation in corn seedlings has been observed 3 days after the addition of weed species of similar height (Ballaré et al., 1990). After five weeks of growing alongside weeds (grown in separate pots to eliminate resource competition), corn seedlings were on average 6cm taller than seedlings grown in a weed-free environment (Rajcan et al., 2004). Similarly, corn subjected to lower ζ beginning at emergence and continuing through four weeks after planting exhibited longer, wider stems, and higher shoot:root ratios (Kasperbauer and Karlen, 1994). Early season exposure to low ζ, even when raised to that of daylight at the 10 leaf tip stage, can reduce kernel number and harvest index in corn (Page et al., 2009).

In living mulch systems, a non-harvested intercrop is grown between rows of a cash crop to provide ecosystem service benefits, such as soil security and water quality. Rows are created for the cash crop through band-applied herbicide or strip tillage, or both. This practice can provide nitrogen to corn, reduce shoulder season nitrate leaching, control runoff and erosion year long, and provide nutritive forage during otherwise fallow periods (Hall et al., 1984a; Grubinger and Minotti, 1990; Singer and Moore, 2010; Ochsner et al., 2010). When adequate living mulch suppression minimizes resource competition with corn, these systems occasionally achieve grain and whole-plant yields similar to monocropping (Duiker and Hartwig, 2004; Wiggans et al., 2012a; Pearson et al., 2014). However, corn yield loss occurs frequently, and there is no consensus as to the mechanism of this yield loss. Research to date has focused on resource competition as a source of this yield loss, yet there has been little work on designing systems that incorporate an understanding of resource-independent competition through light signaling.

The objective of this study was to explore the potential role of tillage width in horizontally propagated ζ and shade avoidance symptoms experienced by corn seedlings. We hypothesized that as tillage widths widen, approaching typical corn spacing (76.2cm), ζ would increase logarithmically, leading to a rapid reduction in shade avoidance symptoms with a marginal increase in tillage width. To test our hypothesis, we characterized the relationship between proximity to a kura clover living mulch and the ζ of horizontally propagated light, and observed shade avoidance characteristics in corn grown at multiple distances from the mulch. In the field, corn was grown under two tillage widths to observe shade avoidance indicators in a production setting, and in a growth chamber, corn seedlings were grown at five distances from living mulch rows to characterize subtle differences in distance and isolate light quality from other sources of interference.

3.2. Materials and Methods

3.2.1. Field site

Field observations were carried out at the Rosemount Research and Outreach Center, 30 miles south of St. Paul, MN. The soil is a well-drained Waukegan silt loam (mesic Typic Hapludoll) with a pH of 6.7 and 4.7% organic matter. Kura clover (var. “Endura”) was established in the 16.2 ha field in 2006, and a corn soybean rotation was integrated into the strip-tilled kura clover living mulch beginning in 2008. In 2015 and 2016, 3200 m^2 were set aside for experimental corn production, and the rest of the field was used for kura clover seed, hay, and honey production.

3.2.2. Field ζ characterization

To characterize the effects of proximity to kura clover on light quality, data were collected during the 2015 growing season using three pairs of horizontally (east-west) oriented single-band radiometers measuring radiation at 660nm and 730nm +/-8 nm (Apogee Instruments, Logan, Utah). Sensors were calibrated by Apogee Instruments before beginning the experiment. Voltage signals ranged from 0mV in darkness to 45-60mV in full sunlight. Signals were converted to photon flux density using sensor-specific calibration factors provided by the manufacturer, with a calibration accuracy of +/- 5%. Sensors were connected in a differential arrangement to a datalogger (CR 1000, Campbell Scientific, Logan, Utah) which recorded red and far red photon flux in μmol m^{-2} s^{-1} and ζ. Five tillage widths were created using a rototiller, and light quality measurements were taken at 10cm above the soil surface on three consecutive weeks in mid spring. In the fall, an additional tillage width was added to the measurements to better characterize the relationship. All light quality measurements were taken under a clear sky within thirty minutes of solar noon.

3.2.3. Corn shade avoidance observation in field

In 2016, seedbeds 15cm and 40cm wide were created using two strip tillage implements in a randomized controlled block design. Seedbed preparations were performed 18 May 2016, according to one of the following treatments: 1) band-kill herbicide burn-down (BK) with 4 kg a.i. ha^{-1} of glyphosate [N-(phosphonomethyl) glycine] with a standard tractor-mounted boom with nozzles set to a 30.5cm spray width, 2) shank tillage (ST) using an Orthman 1tRIPr shank-tillage implement with ground-driven wavy coulters (Orthman Manufacturing Inc., Lexington, NE), 3) rotary zone tillage (RZT) using a custom PTO-driven rotary tine implement (Northwest Tillers, Yakima, WA). Immediately following seedbed preparation, corn hybrid Dekalb DKC 45-65 was seeded at 79,000 seeds ha^{-1} with a six row John Deere 7000 planter (John Deere, Moline, IL). Kura clover was mowed to a height of 5cm prior to corn emergence. Starter fertilizer of 9-18-9 at 56 L ha^{-1} was applied at planting, and in mid-June side dressing of 28% liquid N in occurred (123 kg ha^{1}). To control cool season weeds emerging after corn emergence and suppress kura clover, 1.04 a.i. kg ha^{-1} of glyphosate was broadcast on 2 June 2016. At V3, first internode length, height to 3rd collar, and stem width at first node were measured on six plants per experimental unit with a digital caliper. Morphological measurements were tested for significance using a two-way ANOVA, and means were separated using Fisher's Protected LSD.

3.3. Results and Discussion

3.3.1. Field ζ characterization

The quality of horizontally reflected light 10cm above the soil surface was significantly affected by distance from kura clover living mulch (Figure 7). Incoming solar radiation had a ζ of 1.09, while the ζ of horizontally propagated light approached an asymptote of 0.8. The slope of this relationship was steepest below the 50cm tillage width. Given that corn is commonly planted on 76.2cm rows and popular modern tillage equipment produce seedbeds 15cm wide, this indicates that it is possible to improve the light quality in the cash crop row through wider row preparations.

3.3.2. Corn shade avoidance in field

Corn grown in living mulch tilled at 15cm had longer and thicker first internodes than corn grown in living mulch tilled at 40cm (Table 4; $P = 0.05$). Height to the 3rd collar was not different between treatments. The 1st internode was 2.6 times longer in the 15cm treatment than the 40cm treatment. This suggests shade avoidance syndrome was more pronounced in the period between emergence and V1 than in the period between V2 and V3. Stem diameter, another indicator of shade avoidance, also differed between treatments. Corn plants grown in the 40cm tillage width treatment were 1.9 times thicker than corn plants grown in the 15cm tillage width. As observed by Page et al. (2009), shade avoidance symptoms can include altered root morphology, leaving corn grown under lower ζ to be more prone to resource limitations later in the season.

3.4. Conclusions

Based on these findings, it is likely that narrow tillage widths in kura clover living mulch systems have sufficiently low ζ in the corn row to alter early season corn development. Further research is needed to more fully understand the effects of living mulch suppression strategy on corn yield, especially since scattering and attenuation of light will be affected by living mulch species and management. It may be possible to select crops that have higher tolerance to low ζ and are therefore more suited to living mulch systems. Wider tillage widths may lead to a reduction in ecosystem services and a cost to living mulch health, so as these strategies are explored it will be important to evaluate tradeoffs.

Tables

Table 4- Morphological characteristics indicative of shade avoidance (stem width, height, and length of 1st internode) at the appearance of the third leaf collar grown in corn grown under three contrasting tillage treatments.

	Stem diameter	Length of 1st internode	Height to 3rd leaf collar
Tillage width		(mm)	
0 cm	4.58 (0.49)ǂ b»	58.68 (4.16) a	119.67 (4.91)
15 cm	5.36 (0.54) b	53.42 (6.13) a	121.75 (5.46)
40 cm	8.53 (0.36) a	20.61 (1.47) b	106.00 (4.22)

ǂ Treatment means reported (with standard error).
»Within columns, numbers associated with different letters are different at $P = 0.05$ per Fisher's protected LSD.

This page intentionally left blank

Figures

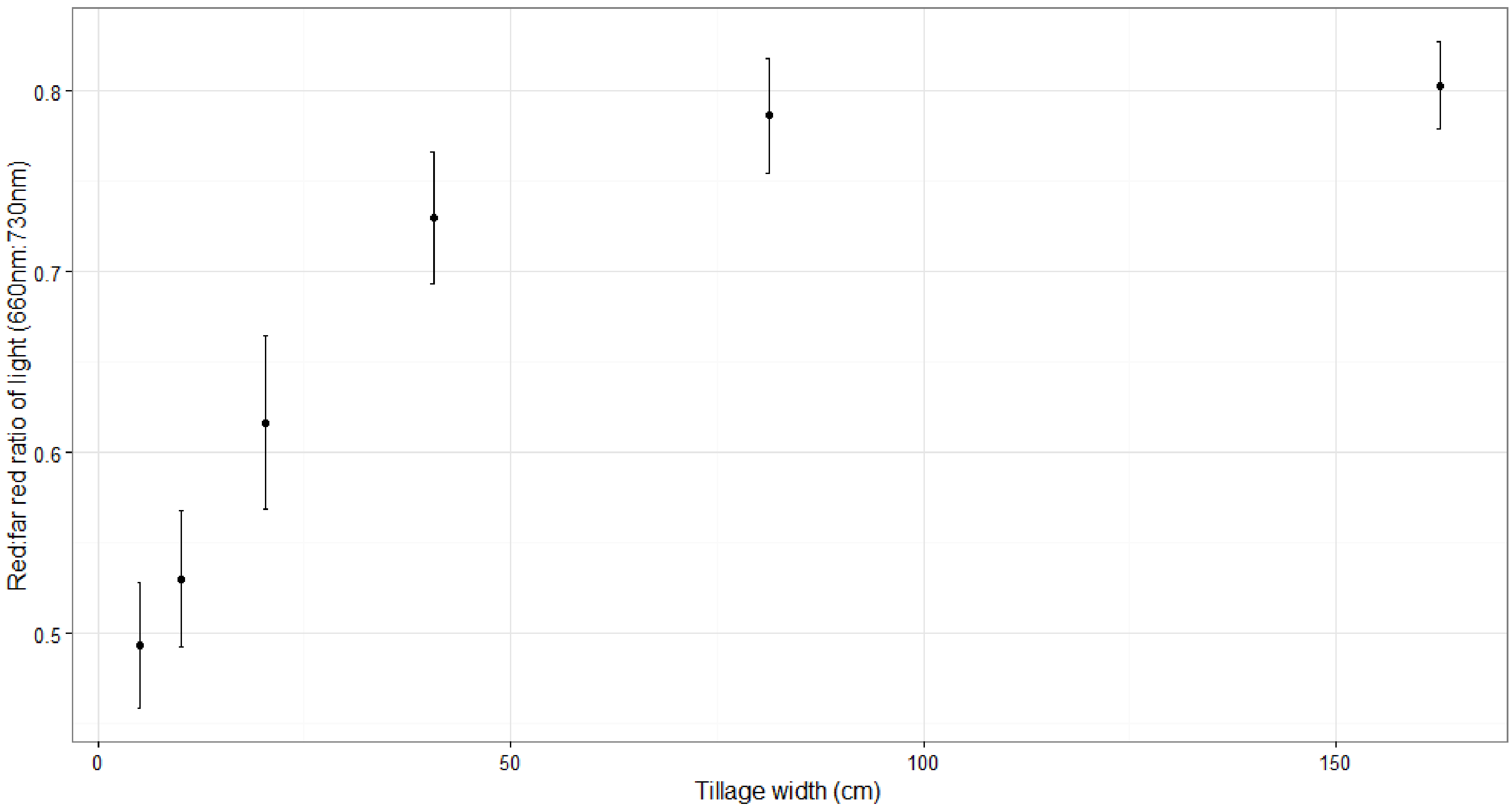

Figure 7- Observed relationship between tillage width and ratio of red:far red light reflected horizontally at 10cm above seed bed in a Kura clover living mulch field. Error bars represent standard error of the mean.

4. References

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn Growth and Development. Iowa State Univ. Ext. OutreachAvailable at https://store.extension.iastate.edu/Product/Corn-Growth-and-Development (verified 25 January 2016).

Affeldt, R.P., K.A. Albrecht, C.M. Boerboom, and E.J. Bures. 2004. Integrating Herbicide-Resistant Corn Technology in a Kura Clover Living Mulch System. Agron. J. 96(1): 247–251Available at https://dl-sciencesocieties-org.ezp1.lib.umn.edu/publications/aj/articles/96/1/247 (verified 22 December 2015).

Afifi, M., and C. Swanton. 2011. Maize seed and stem roots differ in response to neighbouring weeds. Weed Res. 51(5): 442–450Available at http://doi.wiley.com/10.1111/j.1365-3180.2011.00865.x (verified 8 December 2014).

Afzalinia, S., and J. Zabihi. 2014. Soil compaction variation during corn growing season under conservation tillage. Soil Tillage Res. 137: 1–6Available at http://www.sciencedirect.com/science/article/pii/S0167198713002031 (verified 2 January 2015).

Albrecht, K.A.., R.A.. Zemenchik, F. Mourino, and R.P. Affeldt. 2003. Performance of Kura Clover-Based Agricultural Systems.

Alletto, L., Y. Coquet, and E. Justes. 2011. Effects of tillage and fallow period management on soil physical behaviour and maize development. Agric. Water Manag. 102(1): 74–85Available at http://www.sciencedirect.com/science/article/pii/S0378377411002721 (verified 2 January 2015).

Alvarez, R., and H.S. Steinbach. 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil Tillage Res. 104(1): 1–15Available at http://linkinghub.elsevier.com/retrieve/pii/S016719870900052X (verified 2 January 2015).

Andrzejewska, J., K.A. Albrecht, and G. Harasimowicz-Hermann. 2014. Intercropping winter cereals with Caucasian clover for forage in northern Europe. Acta Agric. Scand. Sect. B — Soil Plant Sci. 64(8): 734–740Available at http://www.tandfonline.com/doi/abs/10.1080/09064710.2014.951679 (verified 22 December 2015).

Arbuckle, J.G., and J. Ferrell. 2012. Attitudes Toward Cover Crops in Iowa: Benefits and Barriers Introduction. Iowa State Univ. Ext. Outreach (March): 1–12.

Baker, J.M. 2012. Vegetative propagation of kura clover: A field-scale test. Can. J. Plant Sci. 92(7): 1245–1251Available at http://pubs.aic.ca/doi/abs/10.4141/cjps2012-014 (verified 28 May 2015).

Ballaré, C.L., and J.J. Casal. 2000. Light signals perceived by crop and weed plants. F. Crop. Res. 67(2): 149–160Available at http://www.sciencedirect.com/science/article/pii/S0378429000000903 (verified 12 January 2015).

Ballaré, C.L., A.L. Scopel, and R.A. Sánchez. 1990. Far-red radiation reflected from adjacent leaves: an early signal of competition in plant canopies. Science (80-.). 247(4940): 329–332Available at http://www.jstor.org/stable/pdfplus/2873635.pdf (verified 6 January 2015).

Bard, N.A. 2009. Mechanical and Thermal Suppression of Kura Clover Living Mulch for Corn Production: An Agronomic and Biophysical Analysis.
Berkevich, R. 2008. Corn response to nitrogen fertilizer in kura clover living mulch.
Bescansa, P., M.J. Imaz, I. Virto, A. Enrique, and W.B. Hoogmoed. 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil Tillage Res. 87(1): 19–27Available at http://www.sciencedirect.com/science/article/pii/S0167198705000760 (verified 2 January 2015).
Bryant, W.G. 1974. Caucasian clover (Trifolium ambiguum Bieb.): A review. J. Aust. Inst. Agric. Sci. 40: 11–19.
Burrows, W.C., and W.E. Larson. 1962. Effect of amount of mulch on soil temperature and early growth of corn. Agron. J.
Çakir, R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. F. Crop. Res. 89(1): 1–16Available at http://www.sciencedirect.com/science/article/pii/S0378429004000176 (verified 2 January 2015).
Casal, J.J. 2012. Shade avoidance. Arabidopsis Book 10: e0157Available at http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3350169&tool=pmcentrez&rendertype=abstract.
CERN. 2000. Integrated Assessment of Hypoxia in the Northern Gulf of Mexico. Natl. Sci. Technol. Counc. (May): 58.
Costello, M.J. 1994. Broccoli Growth, Yield and Level of Aphid Infestation in Leguminous Living Mulches. Biol. Agric. Hortic. 10(3): 207–222Available at http://www.tandfonline.com/doi/abs/10.1080/01448765.1994.9754669 (verified 18 December 2016).
Cox, W.J., R.W. Zobel, H.M. van Es, and D.J. Otis. 1990. Tillage Effects on Some Soil Physical and Corn Physiological Characteristics. Agron. J. 82(4): 806Available at https://www-agronomy-org.ezp1.lib.umn.edu/publications/aj/abstracts/82/4/AJ0820040806 (verified 2 January 2015).
Cuomo, G.J., P.R. Peterson, A. Singh, D.G. Johnson, W.A. Head, and M.H. Reese. 2003. Persistence and Spread of Kura Clover in Cool-Season Grass Pastures. Agron. J. 95(6): 1591Available at https://www-agronomy-org.ezp1.lib.umn.edu/publications/aj/abstracts/95/6/1591 (verified 2 January 2015).
Cutforth, H.W., C.F. Shaykewich, and C.M. Cho. 1985. Soil Water- Soil Temperature Interactions in the Germination and Emergence of Corn (Zea mays L.). Can. J. Soil Sci. 65(3): 445–455Available at http://pubs.aic.ca/doi/abs/10.4141/cjss85-048 (verified 2 January 2015).
Demotes-Mainard, S., T. Péron, A. Corot, J. Bertheloot, J. Le Gourrierec, S. Pelleschi-Travier, L. Crespel, P. Morel, L. Huché-Thélier, R. Boumaza, A. Vian, V. Guérin, N. Leduc, and S. Sakr. 2016. Plant responses to red and far-red lights, applications in horticulture. Environ. Exp. Bot. 121: 4–21Available at http://dx.doi.org/10.1016/j.envexpbot.2015.05.010.
Drury, C.F., C.-S. Tan, T.W. Welacky, T.O. Oloya, A.S. Hamill, and S.E. Weaver. 1999. Red Clover and Tillage Influence on Soil Temperature, Water Content, and Corn Emergence. Agron. J. 91: 101Available at https://www-agronomy-org.ezp1.lib.umn.edu/publications/aj/abstracts/91/1/AJ0910010101 (verified 31 December 2014).

Duda, G.P., J.G.M. Guerra, M.T. Monteiro, H. De-Polli, and M.G. Teixeira. 2003. Perennial herbaceous legumes as live soil mulches and their effects on C, N and P of the microbial biomass. Sci. Agric. 60(1): 139–147.
Duiker, S.W., and N.L. Hartwig. 2004. Living mulches of legumes in imidazolinone-resistant corn. Agron. J. 96(4): 1021–1028.
Dunn, M., J.D. Ulrich-Schad, L.S. Prokopy, R.L. Myers, C.R. Watts, and K. Scanlon. 2016. Perceptions and use of cover crops among early adopters: Findings from a national survey. J. Soil Water Conserv. 71(1): 29–40Available at http://www.jswconline.org/cgi/doi/10.2489/jswc.71.1.29.
Eberlein, C.V.C., C.C.C. Sheaffer, and V.F.V. Olivera. 1992. Corn Growth and Yield in an Alfalfa Living Mulch System. J. Prod. Agric. 5(3): 332–339Available at https://www.agronomy.org/publications/jpa/abstracts/5/3/332 (verified 22 December 2014).
Fortin, M.-C. 1993. Soil Temperature, Soil Water, and No-Till Corn Development Following In-Row Residue Removal. Agron. J. 85(92): 571Available at https://www-agronomy-org.ezp3.lib.umn.edu/publications/aj/abstracts/85/3/AJ0850030571 (verified 2 January 2015).
Graven, L.M., and P.R. Carter. 1991. Seed quality effect on corn performance under conventional and no-tillage systems. J. Prod. Agric. 4(3): 366–373.
Grubinger, V.P., and P.L. Minotti. 1990. Managing white clover living mulch for sweet corn production with partial rototilling. Am. J. Altern. Agric. 5(1): 4–12Available at http://journals.cambridge.org.ezp2.lib.umn.edu/action/displayFulltext?type=1&fid=6353780&jid=AJA&volumeId=5&issueId=01&aid=6353772&bodyId=&membershipNumber=&societyETOCSession= (verified 9 November 2015).
Hager, A., and C. Sprague. 2002. Corn Stage Is Critical for Postemergence Herbicide Applications.
Hall, J.K., N.L. Hartwig, and L.D. Hoffman. 1984a. Cyanazine Losses in Runoff from No-Tillage Corn in “Living” and Dead Mulches vs. Unmulched, Conventional Tillage. J. Environ. Qual. 13(1): 105.
Hall, J.K., N.L. Hartwig, and L.D. Hoffman. 1984b. Cyanazine Losses in Runoff from No-Tillage Corn in “Living” and Dead Mulches vs. Unmulched, Conventional Tillage. J. Environ. Qual. 13(1): 105–110.
Hammermeister, A.M. 2015. Organic weed management in perennial fruits. Sci. Hortic. (Amsterdam). 208: 28–42Available at http://dx.doi.org/10.1016/j.scienta.2016.02.004.
Hartwig, N.L., and H.U. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50(6): 688–699.
Holmes, M.G., and H. Smith. 1975. The function of phytochrome in plants growing in the natural environment. Nature 254: 512–514Available at http://www.nature.com/nature/journal/v254/n5500/abs/254512a0.html.
Imholte, A.A., and P.R. Carter. 1987. Planting Date and Tillage Effects on Corn Following Corn1. Agron. J. 79(4): 746Available at https://www-agronomy-org.ezp2.lib.umn.edu/publications/aj/abstracts/79/4/AJ0790040746 (verified 2 January 2015).
Jalota, S.K., V.K. Arora, and O. Singh. 2006. Development and evaluation of a soil water evaporation model to assess the effects of

soil texture, tillage and crop residue management under field conditions. Soil Use Manag. 16(3): 194–199Available at http://doi.wiley.com/10.1111/j.1475-2743.2000.tb00192.x (verified 2 January 2015).

Jama, A.O., and M.J. Ottman. 1993. Timing of the First Irrigation in Corn and Water Stress Conditioning. Agron. J. 85(6): 1159Available at https://www-agronomy-org.ezp3.lib.umn.edu/publications/aj/abstracts/85/6/AJ0850061159 (verified 2 January 2015).

Johnson, M.D., and B. Lowery. 1985. Effect of Three Conservation Tillage Practices on Soil Temperature and Thermal Properties. Soil Sci. Soc. Am. J. 49(6): NPAvailable at https://www-soils-org.ezp3.lib.umn.edu/publications/sssaj/abstracts/49/6/SS0490061547 (verified 2 January 2015).

Jones, R.A., E.A. Rupert, and O.W. Barnett. 1981. Virus Infection of Trifolium Species in Cell Suspension Cultures. 71(2): 116–119.

Kaspar, T.C., D.C. Erbach, and R.M. Cruse. 1990. Corn Response to Seed-Row Residue Removal. Soil Sci. Soc. Am. J. 54(4): 1112Available at https://www-soils-org.ezp3.lib.umn.edu/publications/sssaj/abstracts/54/4/SS0540041112 (verified 2 January 2015).

Kaspar, T.C., E.J. Kladivko, J.W. Singer, S. Morse, and D. Mutch. 2005. Potential and Limitations of Cover Crops, Living Mulches, and Perennials to Reduce Nutrient Losses to Water Sources from Agricultural Fields in the. p. 1–22. *In* Gulf Hypoxia and Local Water Quality Concerns Workshop. Ames, IA.

Kasperbauer, M.J., and D.L. Karlen. 1994. Plant Spacing and Reflected Far-Red Light Effects on Phytochrome-Regulated Photosynthate Allocation in Corn Seedlings. Crop Sci. 34(6): 1564–1569Available at https://dl-sciencesocieties-org.ezp2.lib.umn.edu/publications/cs/abstracts/34/6/CS0340061564 (verified 25 January 2016).

Kelly, T. 2012. Water Recreation Economy at Risk from the Potential Spread of Asian Carp in Minnesota.

Kołota, E., and K. Adamczewska-Sowińska. 2013. Living mulches in vegetable crops production: Perspectives and limitations (a reviev). Acta Sci. Pol. Hortorum Cultus 12(6): 127–142Available at http://www.scopus.com/inward/record.url?eid=2-s2.0-84888127187&partnerID=40&md5=6765d41a2d94e03ae56520b814500dbb (verified 9 November 2015).

Kremer, R.J., and R.D. Kussman. 2011. Soil quality in a pecan-kura clover alley cropping system in the Midwestern USA. Agrofor. Syst. 83(2): 213–223.

Kumwenda, J.D.T., D.E. Radcliffe, W.L. Hargrove, and D.C. Bridges. 1993. Reseeding of Crimson Clover and Corn Grain Yield in a Living Mulch System. Soil Sci. Soc. Am. J. 57: 517.

Kurtz, T., S.W. Melsted, and R.H. Bray. 1952. The Importance of Nitrogen and Water in Reducing Competition Between Intercrops and Corn1. Agron. J. 44(1): 13Available at https://www.agronomy.org/publications/aj/abstracts/44/1/AJ0440010013 (verified 8 October 2016).

Laberge, G., P. Seguin, P.R. Peterson, C.C. Sheaffer, N.J. Ehlke, G.J. Cuomo, and R.D. Mathison. 2005. Establishment of Kura

Clover No-Tilled into Grass Pastures with Herbicide Sod Suppression and Nitrogen Fertilization. Agron. J. 97: 250–256Available at https://www.agronomy.org/publications/aj/articles/97/1/0250?highlight=&search-result=1 (verified 28 May 2015).

Licht, M.A., and M. Al-Kaisi. 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. 80(1–2): 233–249Available at http://www.sciencedirect.com/science/article/pii/S0167198704001011 (verified 2 January 2015).

Liedgens, M., E. Frossard, and W. Richner. 2004. Interactions of maize and Italian ryegrass in a living mulch system: (2) Nitrogen and water dynamics. Plant Soil 259(1–2): 243–258.

Liu, J.G.J., K.J. Mahoney, P.H. Sikkema, and C.J. Swanton. 2009. The importance of light quality in crop-weed competition. Weed Res. 49(2): 217–224Available at http://apps.webofknowledge.com.ezp1.lib.umn.edu/full_record.do?product=UA&search_mode=GeneralSearch&qid=6&SID=2BHEpGsIZY94UGQ5cIR&page=2&doc=18 (verified 13 January 2015).

Malézieux, E., Y. Crozat, C. Dupraz, M. Laurans, D. Makowski, H. Ozier-Lafontaine, B. Rapidel, S. de Tourdonnet, and M. Valantin-Morison. 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agron. Sustain. Dev. 29: 43–62.

Martin, R.C., P.R. Greyson, and R. Gordon. 1999a. Competition between corn and a living mulch. Can. J. Plant Sci. 79(4): 579–586Available at https://atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/3059/P98-089.pdf?sequence=1 (verified 26 December 2014).

Martin, R.C., P.R. Greyson, and R. Gordon. 1999b. Competition between corn and a living mulch. Can. J. Plant Sci. 79(4): 579–586Available at https://atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/3059/P98-089.pdf?sequence=1 (verified 26 December 2014).

Mendiburu, F. de. 2016. agricolae: Statistical Procedures for Agricultural Research. Available at https://cran.r-project.org/package=agricolae.

Minnesota Department of Health. 2015. Minnesota Drinking Water 2015 Annual Report for 2014.

Minnesota Pollution Control Agency. 2013. Nitrogen in Minnesota Surface Waters. (June).

Minnesota Polution Control Agency. 2015. Swimmable, fishable, fixable? What we've learned so far about Minnesota waters. (April): 1–25.

Montgomery, B.L. 2016. Spatiotemporal Phytochrome Signaling during Photomorphogenesis: From Physiology to Molecular Mechanisms and Back. Front. Plant Sci. 7(April): 1–8Available at http://journal.frontiersin.org/article/10.3389/fpls.2016.00480.

Morgan, D.C., and H. Smith. 1979. A systematic relationship between phytochrome-controlled development and species habitat, for plants grown in simulated natural radiation. Planta 145(3): 253–258.

NRCS. 2013. Cover Crop Termination Guidelines.

Ntahimpera, N., M.A. Ellis, L.L. Wilson, and L. V Madden. 1998. Effects of a Cover Crop on Splash Dispersal of Colletotrichum acutatum Conidia. Phytopathology 88(6): 536–43Available at http://apsjournals.apsnet.org/doi/abs/10.1094/PHYTO.1998.88.6.536.

O'Connell, N., and R. Snyder. 1999. Cover crops, mulch lower night temperatures in citrus. Calif. Agric. 53(5): 37–40Available at http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v053n05p37&abstract=yes (verified 22 December 2014).

Ochsner, T.E., K.A. Albrecht, T.W. Schumacher, J.M. Baker, and R.J. Berkevich. 2010. Water Balance and Nitrate Leaching under Corn in Kura Clover Living Mulch. Agron. J. 102(4): 1169Available at https://www-agronomy-org.ezp2.lib.umn.edu/publications/aj/abstracts/102/4/1169 (verified 31 December 2014).

Oguntunde, P.G., A.E. Ajayi, and N. Van De Giesen. 2006. Tillage and surface moisture effects on bare-soil albedo of a tropical loamy sand. Soil Tillage Res. 85(1–2): 107–114.

Olejnik, S., J. Li, S. Supattathum, and C. Huberty. 2016. Multiple Testing and Statistical Power with Modified Bonferroni Procedures. J. Educ. Behav. Stat. 22(4): 389–406.

Page, E.R., M. Tollenaar, E.A. Lee, L. Lukens, and C.J. Swanton. 2009. Does the shade avoidance response contribute to the critical period for weed control in maize (Zea mays)? Weed Res. 49(6): 563–571Available at http://doi.wiley.com/10.1111/j.1365-3180.2009.00735.x (verified 6 January 2015).

Pearson, C.H., J.E. Brummer, A.T. Beahm, and N.C. Hansen. 2014. Kura Clover Living Mulch for Furrow-Irrigated Corn in the Intermountain West. Agron. J. 106(4): 1324Available at https://www.agronomy.org/publications/aj/pdfs/106/4/1324 (verified 22 December 2014).

Pellet, F.C. 1948. That new clover again. Amer. Bee J. 88: 20–22.

Pellett, F.C. 1945. That new clover. Amer. Bee J. 85: 394–395.

Pinheiro J., Bates D., DebRoy S., S.D. and R.C.T. 2016. nlme: Linear and Nonlinear Mixed Effects Models. Available at http://cran.r-project.org/package=nlme.

Prasifka, J.R., N.P. Schmidt, K. a. Kohler, M.E. O'neal, R.L. Hellmich, and J.W. Singer. 2006. Effects of Living Mulches on Predator Abundance and Sentinel Prey in a Corn–Soybean–Forage Rotation. Environ. Entomol. 35(5): 1423–1431.

R Core Team. 2016. R: A language and environment for statistical computing. Available at https://www.r-project.org/.

Raimbault, B.A., and T.J. Vyn. 1991. Crop Rotation and Tillage Effects on Corn Growth and Soil Structural Stability. Agron. J. 83(6): 979–985Available at https://www-agronomy-org.ezp1.lib.umn.edu/publications/aj/abstracts/83/6/AJ0830060979 (verified 2 January 2015).

Rajcan, I., K.J. Chandler, and C.J. Swanton. 2004. Red–far-red ratio of reflected light: a hypothesis of why early-season weed control is important in corn. Weed Sci. 52(5): 774–778Available at http://www.wssajournals.org/doi/abs/10.1614/WS-03-158R (verified

18 December 2014).
Rajcan, I., and C.J. Swanton. 2001. Understanding maize–weed competition: resource competition, light quality and the whole plant. F. Crop. Res. 71(2): 139–150Available at http://www.sciencedirect.com/science/article/pii/S0378429001001599 (verified 15 December 2014).
Ramert, B. 1996. The influence of intercropping and mulches on the occurrence of polyphagous predators in carrot fields in relation to carrot fly (Psila rosae (F)) (Dipt, Psilidae) damage. J. Appl. Entomol. Fur Angew. Entomol. 120(1): 39–46.
Riday, H., and K.A. Albrecht. 2010. Registration of Kura1 (M. Bieb) Germplasm. J. Plant Regist. 4(1): 80Available at https://www.crops.org/publications/jpr/abstracts/4/1/80 (verified 22 December 2015).
Roig-Villanova, I., and J.F. Martínez-García. 2016. Plant Responses to Vegetation Proximity: A Whole Life Avoiding Shade. Front. Plant Sci. 7(February): 1–10.
Rutto, E., C. Daft, J. Kelly, B.K. Chim, J. Mullock, G. Torres, and W. Raun. 2014. Effect of Delayed Emergence on Corn (Zea Mays L.) Grain Yield. J. Plant Nutr. 37(2): 198–208Available at http://www.tandfonline.com/doi/abs/10.1080/01904167.2013.859691.
Salem, H.M., C. Valero, M.Á. Muñoz, M.G. Rodríguez, and L.L. Silva. 2015. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma 237–238: 60–70Available at http://apps.webofknowledge.com.ezp1.lib.umn.edu/full_record.do?product=UA&search_mode=GeneralSearch&qid=16&SID=2DAXHIk5VsSy1lcNwzJ&page=1&doc=2 (verified 9 December 2014).
Sawyer, J.E., P. Pedersen, D.W. Barker, D.A. Ruiz Diaz, and K.A. Albrecht. 2010. Intercropping Corn and Kura Clover: Response to Nitrogen Fertilization. Agron. J. 102(2): 568Available at https://www.agronomy.org/publications/aj/articles/102/2/568?highlight=&search-result=1 (verified 28 May 2015).
Schneider, E.C., and S.C. Gupta. 1985. Corn Emergence as Influenced by Soil Temperature, Matric Potential, and Aggregate Size Distribution. Soil Sci. Soc. Am. J. 49(2): 415–422Available at https://www-soils-org.ezp3.lib.umn.edu/publications/sssaj/abstracts/49/2/SS0490020415 (verified 2 January 2015).
Schwartz, R.C., R.L. Baumhardt, and S.R. Evett. 2010. Tillage effects on soil water redistribution and bare soil evaporation throughout a season. Soil Tillage Res. 110(2): 221–229Available at http://dx.doi.org/10.1016/j.still.2010.07.015.
Scott Flynn, E., K.J. Moore, J.W. Singer, K.R. Lamkey, E.S. Flynn, K.J. Moore, J.W. Singer, and K.R. Lamkey. 2013. Evaluation of grass and legume species as perennial ground covers in corn production. Crop Sci. 53(2): 611–620Available at http://apps.webofknowledge.com/full_record.do?product=UA&search_mode=CitingArticles&qid=7&SID=3DcElHHgwFwtnsVPWEb&page=1&doc=2 (verified 15 December 2014).
Seguin, P., C.C. Sheaffer, N.J. Ehlke, M.P. Russelle, and P.H. Graham. 2001. Nitrogen Fertilization and Rhizobial Inoculation Effects on Kura Clover Growth. Agron. J. 93(6): 1262Available at

https://www.agronomy.org/publications/aj/articles/93/6/1262?highlight=&search-result=1 (verified 28 May 2015).
Sheaffer, C.C., G.C. Marten, R.M. Jordan, and E.A. Ristau. 1992. Forage Potential of Kura Clover and Birdsfoot Trefoil when Grazed by Sheep. Agron. J. 84(2): 176Available at https://dl-sciencesocieties-org.ezp2.lib.umn.edu/publications/aj/abstracts/84/2/AJ0840020176 (verified 11 November 2015).
Siller, A.R.S., K.A. Albrecht, and W.E. Jokela. 2016. Soil erosion and nutrient runoff in corn silage production with Kura clover living mulch and winter rye. Agron. J. 108(3): 989–999.
Singer, J.W., and K.J. Moore. 2010. Living mulch nutritive value in a corn-soybean-forage rotation. Agron. J. 102(1): 282–288.
Singer, J., and P. Pedersen. 2006. Living mulches for corn soybean. (August 2005).
Singh, P., J.Q. Wu, D.K. McCool, S. Dun, C.-H. Lin, and J.R. Morse. 2009. Winter Hydrologic and Erosion Processes in the U.S. Palouse Region: Field Experimentation and WEPP Simulation. Vadose Zo. J. 8(2): 426Available at https://www.soils.org/publications/vzj/abstracts/8/2/426 (verified 2 January 2015).
Smith, H. 1982. Light Quality, Photoperception, and Plant Strategy. Annu. Rev. Plant Physiol. 33: 481–518Available at http://www.annualreviews.org.ezp1.lib.umn.edu/doi/pdf/10.1146/annurev.pp.33.060182.002405 (verified 25 January 2016).
Smith, H., J.J. Casal, and G.M. Jackson. 1990. Reflection Signals and the Perception By Phytochrome of the Proximity of Neighboring Vegetation. Plant Cell Environ. 13(1): 73–78.
Smith, H., and M.G. Holmes. 1977. The Function of Phytochrome in the Natural Environment- iii. Measurement and Calculation of Phytochrome Photoequilibria. Photochem. Photobiol. 25(6): 547–550.
Soane, B.D., B.C. Ball, J. Arvidsson, G. Basch, F. Moreno, and J. Roger-Estrade. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil Tillage Res. 118: 66–87Available at http://dx.doi.org/10.1016/j.still.2011.10.015.
Speer, G.S., and D.W. Allinson. 1985. Kura Clover (Trifolium ambiguum): Legume for Forage and Soil Conservation. Econ. Bot. 39(2): 165–176.
Stewart, A. V., and G.T. Daly. 1980. Growth of an established stand of Trifolium am fertile lowland environment. New Zeal. J. Exp. Agric. 8: 255.
Tan, C.S., C.F. Drury, J.D. Gaynor, T.W. Welacky, and W.D. Reynolds. 2002. Effect of tillage and water table control on evapotranspiration, surface runoff, tile drainage and soil water content under maize on a clay loam soil. Agric. Water Manag. 54(3): 173–188Available at http://www.sciencedirect.com/science/article/pii/S0378377401001780 (verified 2 January 2015).
Teasdale, J.R. 1996. Contribution of Cover Crops to Weed Management in Sustainable Agricultural Systems. J. Prod. Agric. 9(4): 475–479Available at https://www.agronomy.org/publications/jpa/abstracts/9/4/475 (verified 2 October 2016).
Townsend, C.E. 1970. Phenotypic Diversity for Agronomic Characters and Frequency of Self-Compatible Plants in Trifolium

ammbiguum. Can. J. Plant Sci. 338(1471): 331–338.
USDA. 2012. 2012 Census of Agriculture: United States.
USDA/NASS. 2015. 2015 State Agriculture Overview for Minnesota. Census Agric. Vol. 1, Geogr. Area Ser.Available at https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=minnesota.
USDA Economic Research Service. 2016. Corn Overview. Available at https://www.ers.usda.gov/topics/crops/corn/.
Welker, W.V. and D.M.G. 1988. Growth responses of young peach trees and changes in soil characteristics with sod and conventional planting systems. J. Amer. Soc. Hort. Sci. 113: 652–656.
Wiggans, D.R., J.W. Singer, K.J. Moore, and K.R. Lamkey. 2012a. Response of Continuous Maize with Stover Removal to Living Mulches. Agron. J. 104(4): 917–925Available at file:///Users/michelledobbratz/Google Drive/school/Research/Lab/CLC papers/Response of Continuous Maize with Stover Removal to Living Mulches.pdf (verified 9 November 2015).
Wiggans, D.R., J.W. Singer, K.J. Moore, and K.R. Lamkey. 2012b. Maize Water Use in Living Mulch Systems with Stover Removal. Crop Sci. 52(1): 327Available at https://www.crops.org/publications/cs/abstracts/52/1/327 (verified 21 November 2014).
Wilson, G.L., B.J. Dalzell, D.J. Mulla, T. Dogwiler, and P.M. Porter. 2014. Estimating water quality effects of conservation practices and grazing land use scenarios. J. Soil Water Conserv. 69(4): 330–342.
Wyngaarden, S.L., A.C.M. Gaudin, W. Deen, and R.C. Martin. 2015. Expanding red clover (trifolium pratense) usage in the corn-soy-wheat rotation. Sustain. 7(11): 15487–15509.
Xu, D., and A. Mermoud. 2001. Topsoil properties as affected by tillage practices in North China. Soil Tillage Res. 60(1–2): 11–19Available at http://www.sciencedirect.com/science/article/pii/S0167198701001672 (verified 2 January 2015).
Zemenchik, R.A., K.A. Albrecht, C.M. Boerboom, and J.G. Lauer. 2000. Corn production with kura clover as a living mulch. Agron. J. 92(4): 698–705Available at https://www.agronomy.org/publications/aj/articles/92/4/698 (verified 22 December 2014).
Zemenchik, R.A., K.A. Albrecht, and M.K. Schultz. 2001. Nitrogen replacement values of kura clover and birdsfoot trefoil in mixtures with cool-season grasses. Agron. J. 93(2): 451–458.
Ziyomo, C., K.A. Albrecht, J.M. Baker, and R. Bernardo. 2013. Corn Performance under Managed Drought Stress and in a Kura Clover Living Mulch Intercropping System. Agron. J. 105(3): 579Available at https://www.agronomy.org/publications/aj/abstracts/105/3/579 (verified 22 December 2014).
Zumwinkle, M. 1995. Living Mulch Literature Review.

5. **Appendix**

Table 5 - F & P values from Analysis of Variance on select parameters from section 2

parameter	Year	trt	Year	trt:Year	DAP	trt:DAP	Year:DAP	trt:Year:DAP

F	avg temp 0-50d	combined	3.9	350.09	3.668				
		2015	0.312						
		2016	12.347						
	SWP repeated measures 0-50d	combined	0.9841	49.389	1.092	9.8202	0.2132	6.23112	0.17166
		2015	2.5144			32.404	0.5781		
		2016	1.0338			8.0892	0.1917		
	emergence	combined	40.815	39.283	17.059	357.92	15.396	2.0145	5.409
		2015	14.673			149.24	7.3125		
		2016	36.352			217.13	12.567		
	veg	combined	62.635	128.43	37.528	2521.1	3.2489	43.1914	0.5977
		2015	22.224			3740.8	4.183		
		2016	63.783			580.11	1.2093		
	grain	combined	6.445	77.325	5.104				
		2015	1.0516						
		2016	8.3281						
	stover	combined	3.8528	5.9697	2.1686				
		2015	1.1803						
		2016	4.3303						
	kura biomass	combined	1.9546	110.86	0.662	26.669	0.7559	16.5055	0.85841
		2015	0.8467			1.6238	1.0055		
		2016	1.5139			26.507	0.8322		
	kura cover	combined	1.0392	93.478	0.0176	6.75	0.1945	0.8959	0.0253
		2015	0.5405			1.2222	0.0665		
		2016	1.4485			26.332	0.3866		
P	avg temp	combined	0.0087	<.0001	0.0119				
		2015	0.8169						

	2016	<.0001						
SWP 0-50d	combined	0.3993	<.0001	0.3513	0.0018	0.8873	0.0127	0.9156
	2015	0.0573			<.0001	0.6296		
	2016	0.3769			0.0046	0.9021		
emergence	combined	<.0001	<.0001	0.0039	<.0001	<.0001	0.1576	0.0014
	2015	<.0001			<.0001	<.0001		
	2016	<.0001			<.0001	<.0001		
veg	combined	<.0001	<.0001	<.0001	<.0001	0.0234	<.0001	0.6174
	2015	<.0001			<.0001	0.0082		
	2016	<.0001			<.0001	0.3121		
grain	combined	0.0029	<.0001	0.0083				
	2015	0.4162						
	2016	0.0065						
stover	combined	0.0242	0.0235	0.1219				
	2015	0.3705						
	2016	0.0378						
kura biomass	combined	0.1348	<.0001	0.5798	<.0001	0.5249	0.0002	0.4698
	2015	0.4845			0.2172	0.4109		
	2016	0.2401			<.0001	0.4911		
kura cover	combined	0.375	<.0001	0.9968	0.0097	0.9001	0.3444	0.9946
	2015	0.6549			0.2699	0.9776		
	2016	0.2571			<.0001	0.7638		