Soil & Tillage Research 189 (2019) 229–235

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Rotary zone tillage improves corn establishment in a kura clover living mulch

Michelle Dobbratz[a,*], John M. Baker[a,b], Julie Grossman[c], M. Scott Wells[d], Peyton Ginakes[d]

[a] Department of Soil, Water, and Climate, University of Minnesota, 1991 Upper Buford Circle, St. Paul, MN, 55108, United States
[b] USDA-ARS, Soil and Water Management Research Unit, 1991 Upper Buford Circle, Saint Paul, MN, 55108, United States
[c] Department of Horticultural Science, University of Minnesota, 1970 Folwell Ave, Saint Paul, MN, 55108, United States
[d] Department of Agronomy and Plant Genetics, University of Minnesota, 1991 Upper Buford Circle, Saint Paul, MN, 55108, United States

ARTICLE INFO

Keywords:
Kura clover
Trifolium intermedium
Conservation tillage
Corn
Maize
Living muchm
Perennial
Perennial living mulch
Novel tillage
Zone tillage
Band kill
Soil moisture
Soil temperature
Operating costs
Vegetative development
Emergence

ABSTRACT

Kura clover (*Trifolium ambiguum* Bieb.) perennial living mulch is a farming practice designed to pair water quality services and row crop production. In this system, rows are mechanically or chemically killed within a perennial kura clover stand to create a suitable environment for planting a crop. However, yields are often reduced relative to conventional, fully-tilled systems. This hypothesis was tested by using a novel rotary zone tillage unit (RZT) that creates 45 cm wide tilled strips with a depth of 8 cm for each row, with rows spaced 76 cm apart. We compared RZT to three row preparation strategies that have been commonly used in living mulch systems: herbicide band kill (BK), and shank tillage (ST), also known as strip tillage. Shank tillage produced bands that were 40 cm wide and 5 cm deep. We monitored kura clover health, soil moisture & temperature, corn (*Zea mays* L.) emergence, corn development, and corn yield in all three row preparation strategies over two growing seasons. 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. However, in 2016, corn grown in RZT plots not only emerged and developed faster, but also produced 4.0 Mg ha^{-1} more grain and 3.5 Mg ha^{-1} more stover biomass than corn grown in ST and BK plots. Kura clover biomass was not affected by treatment in either year. We conclude that rotary zone tillage is a promising row preparation strategy in kura clover living mulch for corn production with minimal herbicide use.

1. Introduction

It is a formidable challenge to maintain current levels of crop production without negatively affecting water quality. Currently, nutrient loss from row crop production contribute to the eutrophication of local surface water, pollution of subsurface drinking water, and regional environmental challenges such as the hypoxic dead zone in the Gulf of Mexico (Rabalais et al., 2002; Wolfe and Patz, 2002; Minnesota Polution Control Agency, 2015). To reduce these negative water quality impacts, there is a need for innovative production strategies that maintain profitability while minimizing the export of nutrients, agrochemicals, and soil. Maintenance of surface vegetative cover is an effective means to protect soil, but it is challenging to do so in annual row crops (Rundquist and Carlson, 2017). There has been much recent emphasis on winter cover crops, which can be difficult to consistently establish, particularly in regions where there is little time between fall grain harvest and the onset of winter. While winter annual cover cropping is a suitable option for many situations, perennial living mulches provide additional benefits more appropriate for some portions of the landscape. For example, some highly erodible, sloping headlands, especially those near water, could be more thoroughly protected from erosion and off-target nutrient export by the deep roots of a perennial crop. In any event, research on both systems should endeavor to provide producers with a suite of options that promote both economic and environmental sustainability.

Perennial living mulches are one management option that could play a role in preventing runoff, leaching, and erosion in these systems. Living mulches are permanent cover crops that are present alongside row crops during the growing season 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., 1984),

Abbreviations: RZT, rotary zone till; BK, band kill; ST, shank till

* Corresponding author.
E-mail addresses: dobbr001@umn.edu (M. Dobbratz), jbaker@umn.edu (J.M. Baker), jgross@umn.edu (J. Grossman), mswells@umn.edu (M.S. Wells), ginak002@umn.edu (P. Ginakes).

https://doi.org/10.1016/j.still.2019.02.007
Received 24 October 2018; Received in revised form 29 January 2019; Accepted 5 February 2019
Available online 19 February 2019
0167-1987/ © 2019 Elsevier B.V. All rights reserved.

and nitrate leaching by as much as 86% (Liedgens et al., 2004) when compared with conventional practices. Living mulches also can benefit soil health indicators by increasing microbial biomass (Alvarez and Steinbach, 2009), organic matter content (Duda et al., 2003), and aggregate stability (Raimbault and Vyn, 1991). They have also been shown to suppress weeds (Teasdale, 1996) regulate pests and disease (Ramert, 1996; Ntahimpera et al., 1998), and increase water infiltration (Singh et al., 2009). Finally, leguminous living mulches have the capacity to fix nitrogen, which can reduce the fertilization requirements of the row crop (Hall et al., 1984; Grubinger and Minotti, 1990; Duiker and Hartwig, 2004). Living mulches thus have the potential to positively impact the landscape if applied to even a modest portion of the 36 million ha of corn production in the U.S. or the over 197 million ha (FAOSTAT, 2019) of corn in the world, particularly if focused on the most vulnerable lands.

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. Living mulches can reduce commodity crop germination rates (Martin et al., 1999), and lower soil temperatures by 0.5–2.8 °C compared to monocrop production (O'Connell and Snyder, 1999; Singer and Pedersen, 2006), which can reduce row crop yields when compared to conventional production systems (Ochsner et al., 2010). The goal of living mulch management is to support the needs of both species, i.e. – to optimize cash crop yield while maintaining the health of the perennial. A major challenge in this regard is minimizing the effects of the living mulch on the seedbed environment early in the growing season. Before planting the cash crop, living mulches can be suppressed through mowing, grazing, or sub-lethal herbicide application. Cash crop rows can then be prepared for planting through some form of partial width tillage 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 (Martin et al., 1999).

Kura clover (*Trifolium ambiguum)*, a perennial forage legume, has demonstrated potential as a living mulch for corn production (Zemenchik et al., 2000; Affeldt et al., 2004; Pearson et al., 2014), but Sawyer et al. (2010) found that intercropping with kura clover was detrimental to corn establishment, development, and ultimately grain yield. Row preparation and suppression strategies have been tested that have sometimes produced grain yields similar to monocrop corn production (Affeldt et al., 2004). However, in that study corn was only planted for two consecutive years, allowing the clover to recover as a hay crop every third year, a system that is viable for producers with animals needing forage.

While increasing corn yields in perennial living mulch systems will increase income available to the producers, the cost of new technology that could provide those increased yields could potentially offset those gains. Tractors and implements require a considerable upfront investment. Different strategies take different amounts of time, altering labor costs, maintenance of the tractor, and depreciation costs (Lazarus, 2015).

We propose that more aggressive zone tillage prior to planting might be a viable alternative to band herbicide and strip till applications, providing for more suitable seedbed environment, particularly with regard to abiotic factors such as temperature and moisture. We also propose that more aggressive zone tillage will result in higher corn yields while maintaining the health of the kura stand. 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.

2. Materials and methods

2.1. Site and experimental design

Field studies were conducted in 2015 and 2016 at the University of Minnesota Rosemount Research and Outreach Center (44°43′ N, 93°05′ W) on a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive 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 forage production. Four replications were arranged in a randomized complete block design. Experimental units comprised si x 38.7 m rows of corn with 76.2 cm row spacing. Ginakes et al. (2018) used the same experimental design to explore nitrogen dynamics in the kura clover living mulch system.

2.2. Agronomic management

Row preparations were performed 5 May 2015 and 18 May 2016, according to one of the following row preparation treatments: 1) band kill herbicide burn down (BK) using glyphosate [N-(phosphonomethyl) glycine] at a rate that would amount to 4 kg a.i. ha^{-1} if applied at full width applied with a standard tractor-mounted boom with nozzles set to a 30.5 cm spray width, 2) shank-till (ST), also commonly known as strip-till, using an Orthman 1tRIPr shank-tillage implement with ground-driven wavy coulters (Orthman Manufacturing Inc., Lexington, NE) that created a 5 cm deep 40 cm wide tillage zone, and 3) rotary zone tillage (RZT) using a custom PTO-driven rotary tine implement (Northwest Tillers, Yakima, WA) that created 8 cm deep 45 cm wide tilled zones on 76 cm spacing, i.e. – with 31 cm of undisturbed soil and clover in each inter-row (Fig. 1). Immediately following row 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 later mowed to a height of 5 cm prior to corn emergence. Starter fertilizer of 9-18-9 to achieve 67 kg N ha^{-1}, 134 kg P ha^{-1}, and 67 kg K ha^{-1} was applied at planting. In mid-June, side dressing of 28-0-0-5 liquid fertilizer occurred to achieve 145 kg N ha^{-1} and 26 kg S ha^{-1} in 2015 and 123 kg N ha^{-1} and 22 kg S ha^{-1} in 2016. Side dress rates were determined based on plant nitrogen status at time of application with the aim of preventing nitrogen from being a limiting factor for growth. To control weeds and broadly suppress, but not kill, the kura clover, 1.04 a.i. kg ha^{-1} of glyphosate was broadcast on 8 June 2015 and 2 June 2016.

2.3. Data collection and analysis

Kura clover health was assessed pre-treatment, mid-season, and post-harvest. Biomass of kura clover was assessed in between corn rows by harvesting two 0.1 m^2 samples per plot. Kura clover biomass was

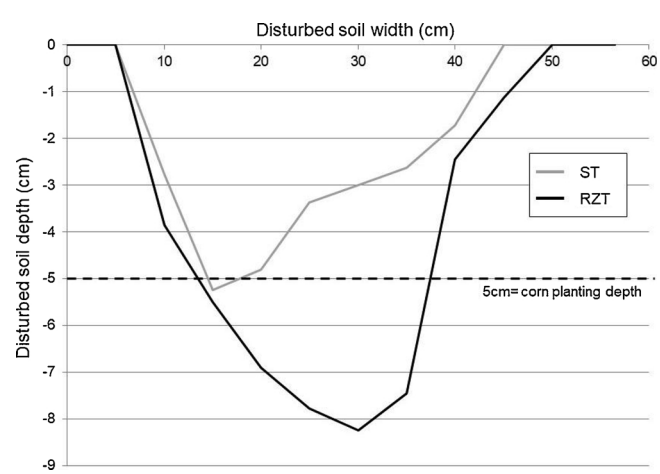

Fig. 1. Diagram of tillage zone in shank till (ST) and rotary zone till (RZT) treatments.

then dried to constant moisture and weighed to determine biomass. Percent cover of kura clover was taken by visual estimate of aerial coverage on a half plot basis; the two observations were averaged to obtain whole plot percent cover. The same rater performed visual estimates at each observation.

Installation of soil sensors occurred within two days of planting. In each plot, two calibrated matric potential and temperature sensors were installed at the 5 cm depth in the seed bed. Half-hour means were logged for the entire growing season. Specific instruments used were MPS-6 soil water potential and temperature sensors, and 5 T M 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 row preparation treatment plots. Corn height was recorded weekly by measuring the distance between the soil surface and the arch of the uppermost unfurled leaf (Hager and Sprague, 2002), beginning at emergence and continuing through the first appearance of tassels. Development was characterized by counting the number of visible leaf collars (Abendroth et al., 2011) from emergence through the seven-leaf stage (V7). Corn stover yield was determined by hand sampling 3 m of row to a height of 15 cm on 9 October 2015 and 24 October 2016. Bundles of corn stover were weighed in the field to determine total wet stover weight. The corn stover was then processed using a wood chipper, homogenized by hand, and subsampled to determine percent moisture. Dry biomass was calculated using wet stover weights and percent moisture. In 2015 hand sampling was conducted by removing cobs from two 3 m lengths of row per plot, shelling, and drying to a consistent weight before adjusting to 15.5% moisture. Grain was harvested mechanically in 2016 with a plot combine and scale on 24 October 2016 and adjusted to 15.5% moisture content.

Economic context was supplied by comparing estimated cost of treatment with estimated increase in income. Estimated cost of treatment was determined by taking the price per hour of tractor ownership and operation and multiplying that by the pace of treatment as reported by the tractor operator. Increase in production was taken as the increase in corn yield multiplied by the cost of corn.

Mixed model analysis ($P = 0.05$) was conducted using R (R Core Team, 2016) to test the effects of year, treatment, and treatment by year interactions for all measurements. Year was significant for all response variables and significant interaction affects between year and treatment were observed for a number of response variables, including corn emergence and development, years were analyzed separately for all parameters. When analyzing emergence rates and vegetative development, days after planting (DAP) were also included in the model. Linear models were constructed using the lme function of the nlme package (Pinheiro et al., 2016), considering treatment, DAP, and their interaction fixed effects and blocks as random effects. No interaction was found between DAP and treatment. When significant differences were found ($P < 0.05$), post-hoc analysis was conducted using Fisher's Protected LSD.

3. Results and discussion

Overall, both growing seasons had warmer temperatures and greater precipitation than the most recent climate normal for the site (Table 1; Midwestern Regional Climate Center and NWS Cooperative Observer Program, 2019). In 2015, total rainfall from May to September was 99 mm (20%) above the 30-yr long-term average. Monthly precipitation in 2015 was consistently above average through July, which was the wettest month. 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 of both years extended the corn growing season and delayed corn harvest. Monthly average temperatures were at or above 30-year averages throughout the duration of the experiment, with September 3 degrees and 2 degrees above average in 2015 and 2016 respectively.

Table 1
Monthly precipitation and mean monthly temperatures for Rosemount, Minnesota. (Midwestern Regional Climate Center, 2018).

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.

3.1. Kura clover

In 2015, kura clover pre-treatment (before tillage or chemical application) dry matter ranged from 933-1365 kg ha^{-1}, while in 2016, kura clover pre-treatment dry matter ranged from 1660-1866 kg ha^{-1} (Table 2), with the higher biomass in 2016 correlated with the later sampling and planting date. In 2015, kura clover biomass production was not impacted by termination treatments at mid-season and post-corn harvest; whereas termination treatment did impact kura biomass performance for the mid-season sampling (Table 2). It is worth noting that the robust kura clover growth in 2016- an average of 630 kg ha^{-1} greater biomass than in 2015- was a factor in the greater variability in soil and corn related parameters discussed below.

Kura clover percent cover was not affected by treatment at the mid-season observation in 2015. At the 2016 post-harvest observation, kura clover percent cover was higher in BK plots than in ST plots, while percent cover in RZT plots was similar to that of both BK and ST. In 2016, kura clover percent cover was similar across all treatments at each time point. These data support our hypothesis that RZT would maintain similar kura clover health compared to other treatments.

3.2. Early season seedbed microclimate

In 2015, mean early season (0–50d) seedbed (5 cm depth) soil water potential in RZT plots was 4.5 kPa greater (wetter) than in BK plots (Table 3). This is contrary to the widespread finding that more intensive tillage lowers soil water availability, in part by promoting evaporation (Xu and Mermoud, 2001; Alletto et al., 2011; Salem et al., 2015). In support of our results, Schwartz et al. (2010) found that in a stubble mulch system, greater evaporation in tilled plots was offset by greater infiltration in no-till plots, suggesting that no-till mulch plots can have similar soil moisture as tilled mulch plots. It has also been observed that, when compared with no till corn in a killed kura clover mulch, living kura clover mulch has little to no effect on drainage (Ochsner et al., 2010). Thus, the effects of zone tillage on soil water holding capacity and competition for seedbed moisture should be studied.

There was no discernible treatment effect on seedbed (5 cm depth) temperature in 2015, while in 2016 seedbed temperatures were impacted by termination treatment through the 95% emergence threshold (0–17 DAP) and through the six leaf stage threshold (0–50 DAP) (Table 3). Compared with the ST treatments, the RZT in 2016 increased seedbed temperature by 0.7 °C during the period of emergence (0–17d) and 0.9 °C during the first 50 days after planting (Table 4). Our 2016 results are comparable to values reported by Licht and Al-Kaisi (2005). Two mechanisms by which increasing tillage intensity can increase soil temperature are removing plant material and lowering the soil albedo (Johnson and Lowery, 1985). While several effects of tillage can

Table 2
Kura clover biomass and percent cover pre-treatment, mid-season, and post-harvest.

Year	Treatment	Biomass			Percent cover		
		Pre-treatment kg ha^{-1}	Mid-season	Post-corn- harvest	Pre-treatment %	Mid-season	Post-corn- harvest
2015	BK	933	258	154	44	49	18 a[†]
	ST	1140	277	159	46	53	11 b
	RZT	1365	141	138	47	50	15 ab
2016	BK	1801	1131	563	75	90	80
	ST	1866	922	556	81	98	81
	RZT	1660	735	463	74	93	80

BK = band kill, ST = shank tillage, and RZT = rotary zone tillage row preparation treatments.
[†] Within columns and years, different letters represent different values per Fisher's Protected LSD ($P < 0.05$).

Table 3
Average soil temperature and soil water potential in seedbed (5 cm depth) through 17 and 50 days after planting.

Year	Treatment	Temperature		Soil water potential	
		0-17d °C	0-50d	0-17d kPa	0-50d
2015	BK	13.7	17.3	−21.7	−25.5 b[†]
	ST	13.6	17.0	−18.7	−22.3 ab
	RZT	13.7	17.2	−19.5	−21.0 a
2016	BK	17.7 b	20.0 b	−64.5	−90.5
	ST	17.8 b	19.7 b	−70.7	−147.9
	RZT	18.5 a	20.6 a	−93.6	−102.5

BK = band kill, ST = shank tillage, and RZT = rotary zone tillage row preparation treatments.
[†] Within columns and years, different letters represent different values per Fisher's Protected LSD ($P < 0.05$).

influence albedo, high soil moisture can overwhelm other effects, and can alter soil temperature on its own (Oguntunde et al., 2006). The abundant soil moisture near the surface in 2015 maintained a low albedo in all treatments, superseding any other effects that treatment might have had on near-surface soil temperatures.

3.3. Corn emergence and early season development

Corn emergence and phenology were impacted by termination treatment in both 2015 ($P < 0.001$) and 2016 ($P < 0.001$; Table 3). Corn in RZT plots reached the 95% emergence threshold one day faster than corn in ST plots in 2015 and three days faster in 2016 (Fig. 2). Since corn emergence and early season development is largely a function of soil temperature and available water (Cutforth et al., 1985; Schneider and Gupta, 1985), the altered seedbed microclimate in RZT plots (Table 3) was associated faster corn emergence and development. The rate of emergence of BK and ST was similar to RZT corn in 2015.

The rate of development of BK and ST was similar to RZT corn in 2015, however in 2016 both the BK and ST developed at a slower rate RZT corn (Fig. 3). This could be explained by the 50% greater productivity of kura clover in 2016 than 2015. Previous work on kura clover living mulch for corn production has found that in years when the kura clover is highly productive, a high rate of glyphosate alone does not always fully terminate kura clover (Affeldt et al., 2004). The BK treatment was, relative to other treatments, more effective in 2015 than 2016, providing better conditions for corn emergence and subsequent development.

Table 4
Yield of corn stover and grain by row preparation treatments in Rosemount, MN.

Year	Treatment	Grain yield[‡] Mg ha^{-1}	Stover yield[§]
2015	BK	14.2	8.6
	ST	13.2	7.5
	RZT	13.7	8.7
2016	BK	6.9 b[†]	5.3 ab
	ST	6.9 b	4.8 b
	RZT	10.9 a	8.3 a

BK = band kill, ST = shank tillage, and RZT = rotary zone tillage row preparation treatments.
[†] Within columns and years, different letters represent different values per Fisher's Protected LSD ($P < 0.05$).
[‡] Corn grain yields are adjusted to moisture content of 155 g kg^{-1}.
[§] Stover yields are reported on a dry matter basis.

3.4. Corn grain and stover yield

Corn grain and stover yields were not impacted by termination treatment in 2015, however the termination treatment had significant effects in 2016 for both parameters ($P < 0.05$; Table 3). In 2015, corn grain yields for all treatments were comparable to the Rosemount Experiment Station mean yield of 13.5 Mg ha^{-1} for bulk corn production (Table 4). In 2016, when corn was planted later in the season than in 2015, the yields were lower overall. Corn grown in the RZT treatment in 2016 produced 4.0 Mg ha^{-1} more grain and 3.5 Mg ha^{-1} more stover than corn grown in ST plots (Table 4- Yield of corn stover and grain by row preparation treatments in Rosemount, MN.Table 4). No pests or diseases were observed in either year. The average yield for all corn at the experiment station was 1.5 Mg ha^{-1} greater in 2015 than 2016, suggesting that less favorable weather during the 2016 corn growing season was partially responsible for the observed yield differences. However, the later planting and the concomitant longer spring growth period for the clover might have been a more important factor – there was more than twice as much kura biomass at planting in 2016 than in 2015 (Table 2). This suggests that the benefit of RZT in mitigating yield loss in warm wet conditions such as those in our experiment will be most noticeable in years when there is more vigorous kura clover growth prior to tillage and planting.

Rutto et al. (2014) observed that for each day corn emergence was delayed, grain yields were reduced by 122 kg ha^{-1}, suggesting that the three-day difference in emergence between treatments in 2016 was responsible for a tenth of the yield difference observed. While the faster corn emergence in the RZT was associated with yield difference in 2016, the magnitude of this difference suggests additional factors, such as warmer soil, more favorable moisture conditions, or more favorable light conditions, or more abundant resources such as nitrogen also contributed to yield gain in the warm, wet conditions of this experiment. Ginakes et al. (2018) found that in the same plots, a combination of ST and RZT resulted in higher soil inorganic nitrogen than BK in 2016, but not in 2015. However, there was no difference observed between ST and RZT for either soil inorganic N or potentially mineralizable N in either year (Ginakes et al., 2018).

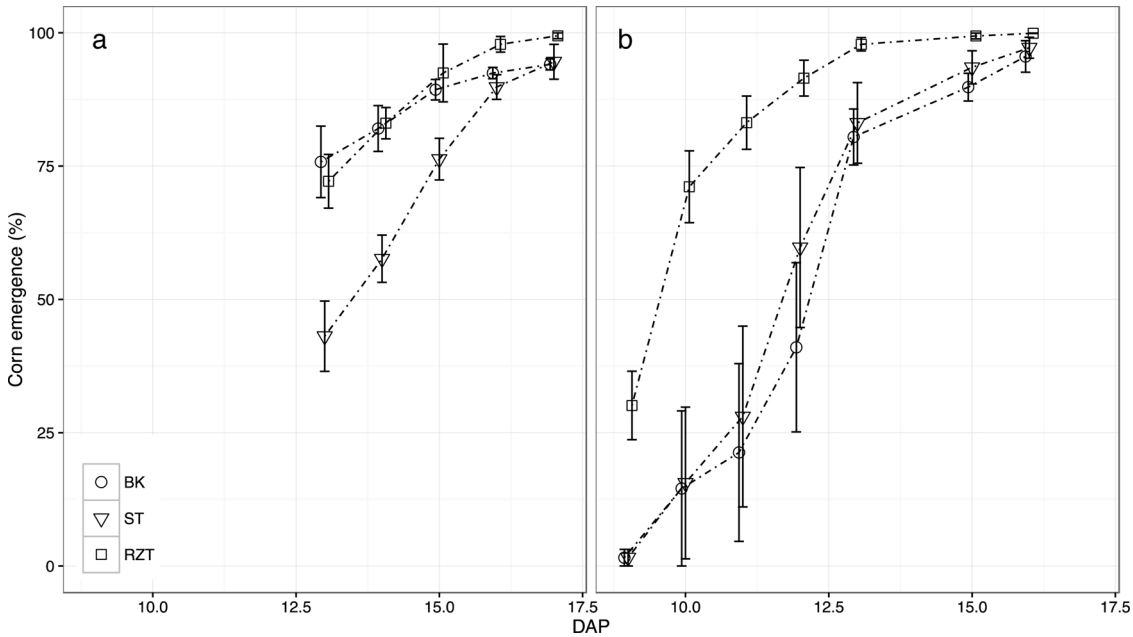

Fig. 2. Corn emergence as a percentage of target population in 2015 (a) and 2016 (b) in a kura clover living mulch, Rosemount, MN. Error bars represent standard error of mean. BK = band kill, ST = shank tillage, and RZT = rotary zone tillage row preparation treatments.

3.5. Economic context of tillage treatments

There are several differences between the conventional strip till unit used in the ST treatment and the custom PTO-driven implement used in the RZT treatment that affect the cost of operation. Most notably, the ST implement can be operated effectively at a higher speed than the RZT implement. In this study on a Waukegan silt loam with few surface rocks, the RZT implement was operated at 1.6 ha hr^{-1} and the ST implement was operated at 2.8 ha hr^{-1}. At \$16.83 hr^{-1}- the 2016 mean wage of an agricultural equipment operator in Minnesota (Bureau of Labor Statistics, 2017) adjusted to include 10% loss of efficiency (Lazarus, 2015), the RZT treatment would cost \$10.84 ha^{-1} and the ST treatment would cost a producer \$5.94 ha^{-1}. Fuel use varies by tractor power, and the horsepower required varies by the attached tillage implement. Due to equipment availability, we used the same 260 hp tractor (John Deere 8260, John Deere, Moline IL), which is required for the RZT implement, for both the RZT and ST implements. However, a 160 hp tractor is sufficient to tow the ST implement. The non-labor costs associated with owning and operating a 260 hp that moves at 1.6 ha hr^{-1} are \$19.43 ha^{-1} for fuel and oil, \$2.98 ha^{-1} for maintenance, \$28.23 ha^{-1} in depreciation, and \$15.30 ha^{-1} in overhead (Lazarus, 2015). For a 160 hp tractor operating at 2.8 ha hr^{-1}, the non-labor costs associated with ownership and operation are \$6.83 ha^{-1} in fuel and oil, \$2.13 ha^{-1} in maintenance, \$7.85 ha^{-1} in depreciation, and \$4.21 ha^{-1} in overhead (Lazarus, 2015). Thus, we estimate the RZT costs an additional \$49.51 ha^{-1} in tractor ownership and operation. At

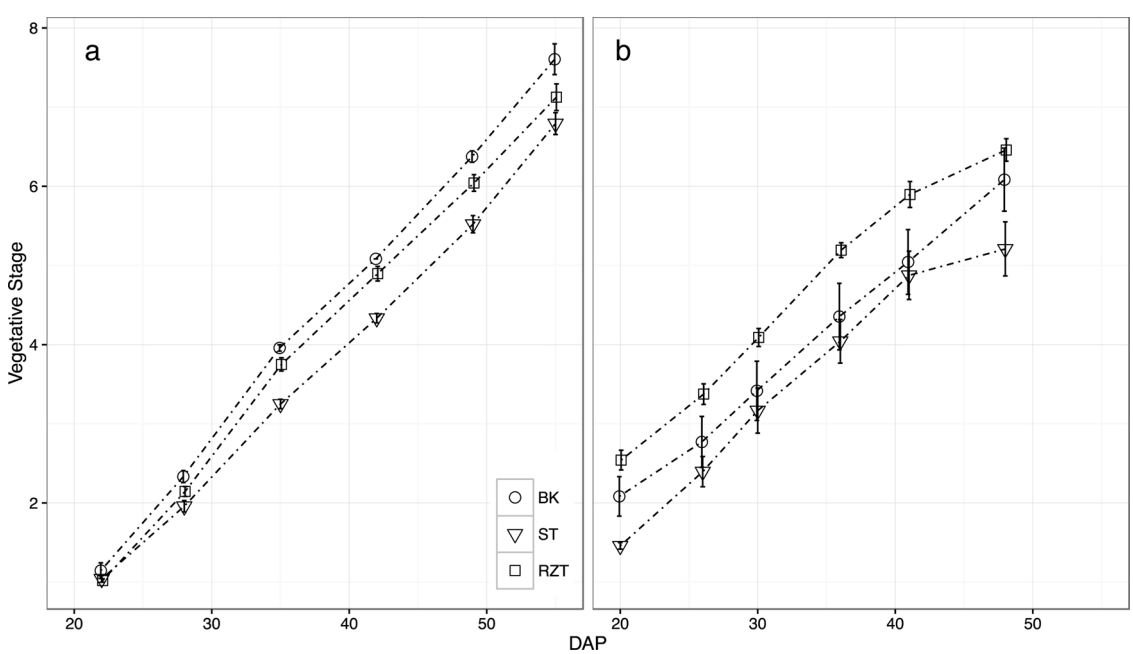

Fig. 3. Mean vegetative stage of corn plants, as determined by number of visible leaf collars in 2015 (a) and 2016 (b) in a kura clover living mulch, Rosemount, MN. Error bars represent standard error of mean. BK = band kill, ST = shank tillage, and RZT = rotary zone tillage row preparation treatments.

the September 2015 price of corn, In 2015 there was no significant difference in yield among treatments and hence no difference in income, while in 2016 the 4 Mg ha^{-1} yield bump provided by the RZT would have resulted in an additional \$507.05 ha^{-1} at the September 2016 price (USDA-NASS, 2018). The tillage implements themselves also have variable costs of ownership (most notably overhead and depreciation) not included here

4. Conclusion

Our results indicate that RZT is a promising strategy for managing kura clover living mulch in corn systems in warm, wet conditions such as this experiment. Living mulch management requires careful attention, particularly during the early season. Corn grown in rows prepared with RZT developed faster than corn grown in rows prepared using ST and BK in 2016, and this increase in development rate was associated with warmer early season seedbed temperatures and faster emergence observed in that year. This had no impact on grain yield in 2015, but was accompanied by grain yields for RZT that exceeded those of BK and ST in 2016, when the living mulch biomass was much greater at planting. The additional kura clover biomass in 2016 was associated with reduced tillage that delayed emergence and development of corn grown in ST and BK plots.

In general, kura clover as a living mulch offers an option to producers looking for multiple benefits. Kura clover can provide forage, and the intercropped system allows for stover removal without carbon loss. This system offers protection in situations where producers grown grain crops in vulnerable areas, such as protect slopes, stream banks, or wellheads. Because of the need for a multi-faceted herbicide strategy to chemically control kura clover, rotary zone tillage is a compelling strategy for managing perennial living mulches on vulnerable lands for water quality benefits.

Compared with band kill, rotary zone tillage appears to be a more reliable strategy for producing grain corn in a kura clover living mulch. While RZT is more expensive than other tillage options, the lower risk of yield reduction could make intercropping more palatable to producers. Given the potential to bolster ecosystem services in niche areas, novel tillage may be attractive to cost sharing programs. Further research across multiple environments and years, particularly dry years, is needed to fully assess the consistency of RZT and possible applications across the landscape. We also observed that the interrows created by RZT persist. In both yeart, interrows were prominent for at least a month after tillage, and it was clear the following spring where the tillage had occurred. The use of RZT every second or third year, with less aggressive tillage, or no-till planting in the intervening years (along with mowing and chemical suppression) should be explored.

Acknowledgements

We thank the staff at the University of Minnesota, Rosemount Research and Outreach Center, and the USDA-ARS for technical support. This project was funded by Minnesota Clean Water Land and Legacy Amendment funds administered by the Minnesota Department of Agriculture , USA.

References

Abendroth, L.J., Elmore, R.W., Boyer, M.J., Marlay, S.K., 2011. Corn Growth and Development. Iowa State Univ. Ext., Outreach.
Affeldt, R.P., Albrecht, K.A., Boerboom, C.M., Bures, E.J., 2004. Integrating herbicide-resistant corn technology in a kura clover living mulch system. Agron. J. 96 (1), 247–251. https://doi.org/10.2134/agronj2004.2470.
Alletto, L., Coquet, Y., Justes, E., 2011. Effects of tillage and fallow period management on soil physical behaviour and maize development. Agric. Water Manage. 102 (1), 74–85. https://doi.org/10.1016/j.agwat.2011.10.008.
Alvarez, R., Steinbach, H.S., 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), 1–15. https://doi.org/10.1016/j.still.2009.02.005.
Bureau of Labor Statistics, 2017. Minnesota - May 2016 OES State Occupational Employment and Wage Estimates.
Cutforth, H.W., Shaykewich, C.F., Cho, C.M., 1985. Soil water- soil temperature interactions in the germination and emergence of corn (Zea mays L.). Can. J. Soil Sci. 65 (3), 445–455. https://doi.org/10.4141/cjss85-048.
Duda, G.P., Guerra, J.G.M., Monteiro, M.T., De-Polli, H., Teixeira, M.G., 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. https://doi.org/10.1590/S0103-90162003000100021.
Duiker, S.W., Hartwig, N.L., 2004. Living mulches of legumes in imidazolinone-resistant corn. Agron. J. 96 (4), 1021–1028.
FAOSTAT. 2019.
Ginakes, P., Grossman, J.M., Baker, J.M., Dobbratz, M., Sooksa-nguan, T., 2018. Soil carbon and nitrogen dynamics under zone tillage of varying intensities in a kura clover living mulch system. Soil Tillage Res. 184. https://doi.org/10.1016/j.still.2018.07.017.
Grubinger, V.P., Minotti, P.L., 1990. Managing white clover living mulch for sweet corn production with partial rototilling. Am. J. Altern. Agric. 5 (1), 4–12. https://doi.org/10.1017/S0889189300003155.
Hager, A., Sprague, C., 2002. Corn Stage Is Critical for Postemergence Herbicide Applications.
Hall, J.K., Hartwig, N.L., Hoffman, L.D., 1984. Cyanazine losses in runoff from no-tillage corn in "living" and dead mulches vs. unmulched, conventional tillage. J. Environ. Qual. 13 (1), 105–110.
Johnson, M.D., Lowery, B., 1985. Effect of three conservation tillage practices on soil temperature and thermal properties. Soil Sci. Soc. Am. J. 49 (6). https://doi.org/10.2136/sssaj1985.03615995004900060067x.
Lazarus, W.F., 2015. Machinery Cost Estimates. Univ. Minnesota Ext., pp. 1–8.
Licht, M.A., Al-Kaisi, M., 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. 80 (1–2), 233–249. https://doi.org/10.1016/j.still.2004.03.017.
Liedgens, M., Frossard, E., Richner, W., 2004. Interactions of maize and Italian ryegrass in a living mulch system: (2) Nitrogen and water dynamics. Plant Soil 259 (1–2), 243–258. https://doi.org/10.1023/B:PLSO.0000020965.94974.21.
Martin, R.C., Greyson, P.R., Gordon, R., 1999. Competition between corn and a living mulch. Can. J. Plant Sci. 79 (4), 579–586. https://doi.org/10.4141/P98-089.
Midwestern Regional Climate Center, 2018. Minneapolis/ St. Paul Airport Global Historical Climatology Network. https://mrcc.illinois.edu/CLIMATE/.
Midwestern Regional Climate Center, NWS Cooperative Observer Program, 2019. cliMATE: MRCC Application Tool.
Minnesota Polution Control Agency, 2015. Swimmable, Fishable, Fixable? What We've Learned so Far About Minnesota Waters (April). pp. 1–25.
Ntahimpera, N., Ellis, M.A., Wilson, L.L., Madden, L.V., 1998. Effects of a cover crop on splash dispersal of colletotrichum acutatum conidia. Phytopathology 88 (6), 536–543. https://doi.org/10.1094/PHYTO.1998.88.6.536.
O'Connell, N., Snyder, R., 1999. Cover crops, mulch lower night temperatures in citrus. Calif. Agric. 53 (5), 37–40.
Ochsner, T.E., Albrecht, K.A., Schumacher, T.W., Baker, J.M., Berkevich, R.J., 2010. Water balance and nitrate leaching under corn in kura clover living mulch. Agron. J. 102 (4), 1169. https://doi.org/10.2134/agronj2009.0523.
Oguntunde, P.G., Ajayi, A.E., Van De Giesen, N., 2006. Tillage and surface moisture effects on bare-soil albedo of a tropical loamy sand. Soil Tillage Res. 85, 107–114. https://doi.org/10.1016/j.still.2004.12.009.
Pearson, C.H., Brummer, J.E., Beahm, A.T., Hansen, N.C., 2014. Kura clover living mulch for furrow-irrigated corn in the intermountain west. Agron. J. 106 (4), 1324. https://doi.org/10.2134/agronj13.0598.
Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., 2016. Nlme: Linear and Nonlinear Mixed Effects Models.
R Core Team, 2016. R: A Language and Environment for Statistical Computing.
Rabalais, N.N., Turner, R.E., Dortch, Q., Justic, D., Bierman, V.J.J., et al., 2002. Nutrient-enhanced productivity in the northern Gulf of Mexico: past, present and future. Hydrobiologia 475/476, 39–63.
Raimbault, B.A., Vyn, T.J., 1991. Crop rotation and tillage effects on corn growth and soil structural stability. Agron. J. 83 (6), 979–985. https://doi.org/10.2134/agronj1991.00021962008300060011x.
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. https://doi.org/10.1111/j.1439-0418.1996.tb01565.x.
Rundquist, S., Carlson, S., 2017. Mapping Cover Crops on Corn and Soybeans in Illinois, Indiana and Iowa: 2015–2016.
Rutto, E., Daft, C., Kelly, J., Chim, B.K., Mullock, J., et al., 2014. Effect of delayed emergence on corn (Zea Mays L.) grain yield. J. Plant Nutr. 37 (2), 198–208. https://doi.org/10.1080/01904167.2013.859691.
Salem, H.M., Valero, C., Muñoz, M.Á., Rodríguez, M.G., Silva, L.L., 2015. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma 237–238, 60–70. https://doi.org/10.1016/j.geoderma.2014.08.014.
Sawyer, J.E., Pedersen, P., Barker, D.W., Ruiz Diaz, D.A., Albrecht, K.A., 2010. Intercropping corn and kura clover: response to nitrogen fertilization. Agron. J. 102 (2), 568. https://doi.org/10.2134/agronj2009.0392.
Schneider, E.C., Gupta, S.C., 1985. Corn emergence as influenced by soil temperature, matric potential, and aggregate size distribution. Soil Sci. Soc. Am. J. 49 (2), 415–422. https://doi.org/10.2136/sssaj1985.03615995004900020029x.
Schwartz, R.C., Baumhardt, R.L., Evett, S.R., 2010. Tillage effects on soil water

redistribution and bare soil evaporation throughout a season. Soil Tillage Res. 110 (2), 221–229. https://doi.org/10.1016/j.still.2010.07.015.
Singer, J., Pedersen, P., 2006. Living Mulches for Corn Soybean. August 2005. .
Singh, P., Wu, J.Q., McCool, D.K., Dun, S., Lin, C.-H., et al., 2009. Winter hydrologic and Erosion processes in the U.S. Palouse region: field experimentation and WEPP simulation. Vadose Zone J. 8 (2), 426. https://doi.org/10.2136/vzj2008.0061.
Teasdale, J.R., 1996. Contribution of cover crops to weed management in sustainable agricultural systems. J. Prod. Agric. 9 (4), 475–479. https://doi.org/10.2134/jpa1996.0475.
USDA-NASS, 2018. Quick Stats.
Wolfe, A.H., Patz, J.A., 2002. Reactive nitrogen and human health : acute and long-term implications. AMBIO J. Hum. Environ. 31 (2), 120–125.
Xu, D., Mermoud, A., 2001. Topsoil properties as affected by tillage practices in North China. Soil Tillage Res. 60 (1–2), 11–19. https://doi.org/10.1016/S0167-1987(01)00167-2.
Zemenchik, R.A., Albrecht, K.A., Boerboom, C.M., Lauer, J.G., 2000. Corn production with kura clover as a living mulch. Agron. J. 92 (4), 698–705. https://doi.org/10.2134/agronj2000.924698x.