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ORIGINAL ARTICLE

Tillage intensity influences nitrogen cycling in organic kura clover living mulch

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Abstract Perennial cover crops, also known as living mulches, have the capacity to improve soil quality, yet their effects on nitrogen (N) cycling and provisioning in organic systems are not well understood. We evaluated soil N contributions of kura clover (*Trifolium ambiguum*) between and within crop rows for four zone tillage approaches of varying intensity for corn (*Zea mays*). In 2015 and 2016, an established kura clover field was subjected to tillage treatments including no-till, traditional shank till, also known as strip-till (ST), novel, PTO-driven rotary zone till (ZT), and a combination of ST and ZT (DT; double till) in Rosemount, MN, followed by corn. An earlier planting date in 2015 (May 5, 2015 vs. May 18, 2016) contributed to a substantially lower rate of kura clover biomass at corn planting in 2015 (518 kg ha^{-1}) compared to 2016 (3035 kg ha^{-1}). The substantial difference in kura clover biomass contributions at tillage and planting between years appeared to govern N cycling indicators. For instance, soil inorganic N differed by tillage treatments only in 2016. After tillage, within row soil inorganic N was 68% and 106% greater than between rows for ST and DT treatments, respectively. At harvest, DT within row soil inorganic N was approximately double that of ST. We conclude that the N benefit from a legume living mulch depends on both the intensity of tillage and the amount of biomass present, and thus there may be advantages to delayed planting, particularly when used for organic production.

Keywords Kura clover · Zone tillage · Living mulch · Soil inorganic nitrogen · Organic agriculture · Legume

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Introduction

The use of kura clover (*Trifolium ambiguum*), a long-lived and rhizomatous perennial, has been proposed as a living mulch option for growers in the Upper Midwest, due to its capacity to diversify farmscapes

(Ochsner et al. 2010), withstand extreme cold (Sheaffer and Marten 1991; Zemenchik et al. 2000), contribute biologically fixed nitrogen (N) to cash crops (Scott et al. 1987; Seguin et al. 2001; Grabber and Jokela 2013), and mitigate agricultural externalities such as soil runoff and nitrate loading in water bodies (Ochsner et al. 2010; Sawyer et al. 2010; Qi et al. 2011; Siller et al. 2016). Living mulches are perennial cover crops that remain between crop rows during growing seasons, and offer benefits that align with mandates for organic production as stated by the National Organic Program (NOP), such as increasing soil biological activity, organic matter, and fertility through the use of cover crops. Zone tillage is a form of reduced tillage that is a compromise between full-width, conventionally intensive tillage and no-till practices. Because living mulches necessitate perennial ground cover maintenance between crop rows during the growing season, zone tillage is employed in order to prepare the narrow planting region where crops will be sown.

As a legume, kura clover has the capacity to contribute new N to crops via biological N fixation, with total amounts delivered dependent on overall plant biomass production. Reported kura clover N fixation rates range widely, from 13 to 276 kg N ha^{-1}, depending on inoculation, location, and soil type (Seguin et al. 2000, 2001; Grabber and Jokela 2013). Compared to systems using full-width tillage, N provided by zone-tilled kura clover is likely localized to the crop seedbed, reducing nitrate leaching losses by concentrating N delivery only to where it is needed within crop rows (Qi et al. 2011; Lowry and Brainard 2016; Alexander et al. 2019). The degree to which N-rich biomass from kura clover serves to meet cash crop needs is not well understood, especially using tillage approaches of varying intensity.

Weed management in no-till agriculture has proven especially difficult for organic production, since synthetic herbicide use is prohibited. Living mulches combined with zone tillage provide a practical opportunity for organic growers to minimize soil disturbance while maintaining ground cover to reduce weed pressure between rows. Their capability to outcompete weeds has been effective in some cases (Enache and Ilnicki 1990; Brandsæter et al. 1998), though usually less reliable than tillage or chemical suppression counterparts (Mohammadi et al. 2012; Brainard et al. 2013). Zone tillage has also been shown to warm the soil seedbed in spring for areas with long and cold winters (Licht and Al-Kaisi 2005; Dobbratz et al. 2019) compared to no tillage or tillage with less soil disturbance and greater plant coverage (Leavitt et al. 2011).

One major barrier to the adoption of zone-tilled living mulches for organic production is the encroachment of vegetative regrowth into the crop row during the growing season following zone creation in the spring, which may compete with cash crop productivity. In conventional systems, living mulch encroachment during the growing season is controlled with herbicides, while in organic systems synthetic herbicides are prohibited and mechanical approaches are required. Traditional zone tillage implements generally consist of shanks that cut narrow slices into the crop row while pushing aside surface residue with ground-driven coulters (e.g., 1tRiPr, Orthman Mnfg., Lexington, NE). Using traditional strip till implements, the width of disturbed soil in the planting bed has been shown to be relatively narrow in living mulch systems, leading to significant regrowth and thus competition between cash crop and living mulch vegetation (Dobbratz et al. 2019). To address this, we evaluated a continuum of tillage approaches of varying soil disturbance intensities. The objectives of this research were to (1) assess the effect of tillage approaches on the contribution of kura clover to available soil N, and (2) evaluate the effect of tillage approaches on corn (*Zea mays*) yields. We hypothesized that treatments using tillage approaches with greater levels of disturbance would increase soil N delivery via increased legume biomass incorporation, as well as reduce competition between kura clover and corn, leading to greater yields.

Materials and methods

Site description

This study was conducted at the University of Minnesota Rosemount Research and Outreach Center, located in Rosemount, MN in 2015 and 2016 (44°71′N, 93°7′W). The soil at Rosemount is a Waukegan silt loam (fine-silty over skeletal mixed, super active, mesic Typic Hapludoll). At the beginning of the experiment, the field had been in established kura clover for 8 years. The field had been managed as a perennial living mulch with annual zone-tilled plantings of conventional corn or soybean until early 2015, when this experiment was initiated. Tilled zones were consistent during the 6 years prior to the experiment, and kura clover and weeds were typically suppressed using broadcast glyphosate [*N*-(phosphonomethyl)glycine] at approximately 1 a.i. kg ha^{-1} during this timeframe.

Experiment design

The experiment used a randomized complete block design with four tillage treatments, each replicated four times. Tillage treatments include no-till (NT), shank till (ST), a novel rotary zone till (ZT), and double till (DT; both shank and rotary zone till). Plots were six rows wide, measuring 9.1 by 4.6 m total. All data were collected from the middle 6.1 m of the two central rows in each plot. Each spring, plots were fertilized ahead of spring tillage and planting with 10 kg N ha^{-1}, 103 kg P ha^{-1}, and 174 kg K ha^{-1}, using Organic Materials Review Institute (OMRI)—listed phosphate rock (0.4-3.9-1.5, 2643 kg ha^{-1} total) and sulfate of potash (0-0-51, 263 kg ha^{-1} total; Table 1) fertilizers. Minimal N source was applied in 2015, to avoid interference with N cycling measurements meant to capture kura clover decomposition. In 2016, however, 483 kg ha^{-1} OMRI-listed 12-0-0 bloodmeal was additionally applied as a sub-plot fertility treatment, totaling 68 kg N ha^{-1} (68 N vs. 10 N), after tillage and prior to corn planting, in response to poor 2015 corn yields. All soils data were collected only from the 10 N sub-plot, but corn yield data were collected from both 10 N and 68 N in order to determine whether N was a limiting factor for corn growth. Depth and width of the tilled zone in ST and ZT treatments are detailed in Dobbratz et al. (2019).

Table 1 Dates of field operations

Operation	Date	
	2015	2016
Applied fertilizer	24 Apr.	8 May
Sampled pre-till biomass	30 Apr.	9 May
Sampled pre-till soil	30 Apr.	11 May
Applied tillage treatments	4 May	18 May
Planted corn	5 May	18 May
Sampled post-till soil	19 May	27–29 May
Mowed between rows	19 June	20 July
Sampled mid-season biomass	20 Aug.	26 July
Sampled harvest biomass	2 Oct.	4 Oct.
Sampled harvest soil	9 Oct.	4 Oct.
Harvested corn	9 Oct.	12 Oct.

Kura clover management

Kura clover in this field was seeded in 2006. The year prior to our experiment (2014), the field was planted to zone-tilled soybean, and zones were maintained for our experiment in 2015. In 2016, the experiment location was moved adjacent to the 2015 plot due to post-harvest slug damage to clover. The 2016 plot had also been planted to zone-tilled soybean in 2014, but was undisturbed in 2015. Kura clover and weed biomass were sampled three times per year: (1) before spring tillage (pre-till), (2) mid corn growing season (mid-season), and (3) at corn harvest (harvest; Table 1). At each sampling time, aboveground biomass was removed both within rows and between rows using a 0.1 m^2 polyvinyl chloride quadrat. When present, weeds were collected and processed separately from clover. Samples were dried at 60 °C for at least 48 h, until a constant weight was achieved, then were weighed, ground, sieved to 1 mm for analysis, and analyzed on a combustion analyzer for C and N content (Elementar VarioMAX CN analyzer, Elementar Americas).

Corn management

Each spring, rows were prepared according to tillage treatment (Table 1). The shank till implement was an Orthman 6-row 1tRiPr (Lexington, NE), and the PTO-driven rotary zone till implement was custom made by Northwest Tillers (Yakima, WA). Corn (Organic Viking Corn, O35-99 N, Albert Lea Seed House, Albert Lea, MN) was planted using a John Deere 7000 planter on a 76 cm row spacing at 79,000 seeds ha^{-1} (Table 1). Because the focus of this study was the effect of zone tillage strategies on kura clover N contributions for corn, within row weeds were removed weekly by hand until corn closed canopy, and between row kura clover was mowed once mid-season in order to reduce encroachment on the rows (Table 1). Corn was hand harvested by removing ears from plants in two 3 m long areas in the two central rows of each plot. When present, grain was removed from cobs to obtain grain yield. If cob had no grain, it was added to stalks for a stover yield. Stalks were cut at ground level, chipped, and a subsample collected (Table 1). Both grain and stover were weighed wet, dried at 60 °C for at least 48 h, and weighed again. Stover was then ground to 1 mm, and the grain was chipped and ground to a powder. Both were analyzed on an Elementar VarioMAX CN (Elementar Americas).

Soil sampling

In order to assess short-term changes in N, soil was sampled three times each growing season: (1) before spring tillage (pre-till), (2) within 15 days after spring tillage (post-till), and (3) at corn harvest (harvest; Table 1). At each time point, the top 15 cm of soil was collected from both in and between rows by taking ten composite samples with a 32 mm diameter soil probe (Oakfield Apparatus Model LS, Fond du Lac, WI), mixing in a bucket, and then removing two subsamples. One subsample was dried at 35 °C for at least 48 h before grinding and sieving to 2 mm, and was used for C/N analysis (Elementar VarioMAX CN analyzer, Elementar Americas). The other subsample was sieved to 2 mm and kept field-moist at 4 °C for inorganic N extractions and potentially mineralizable N (PMN) incubations.

Soil inorganic N

Inorganic N (NH_4^+ and NO_3^-) was measured using a KCl extraction (Robertson et al. 1999). Briefly, 10 g field-moist soil was weighed into 50 mL centrifuge tubes, 40 mL 1 M KCl was added, and tubes were shaken for 1 h at approximately 180 rpm. Samples were allowed to settle for at least 1 h, and supernatant was filtered through #42 Whatman papers and collected in scintillation vials. Vials were frozen for analysis, which was later performed on a Shimadzu TOC and TN analyzer (Kyoto, Japan).

Potentially mineralizable N

Post-till soils in 2016 were analyzed for PMN using a 28d aerobic incubation method (adapted from Scott et al. 1998). Ten grams of soil were weighed into 50 mL centrifuge tubes, and approximately 10 mL water was added, until water holding capacity was reached. Tubes were loosely capped and placed into a plastic bin containing approx. 3 cm water at the bottom. The bin was kept at 37 °C for 28 days. Three times per week, tubes were weighed and soil moisture was amended accordingly. At the end of the incubation, 40 mL of 1.3 M KCl was added to each tube, and they were shaken at approximately 180 rpm for 1 h. The extract was filtered through #42 Whatman filter papers, collected, and frozen. Extracts were analyzed on a Shimadzu TOC and TN analyzer (Kyoto, Japan), and final values were determined by subtracting previously measured inorganic N values from incubation values.

Weather

The 2015 growing season was comparable to the area's 30-year mean temperature, averaging 1 °C cooler in the summer months but remaining warmer than the mean for Sep-Oct, as reported by the National Centers for Environmental Information (NOAA; Table 2). It was wetter than average, especially in July when rainfall exceeded the 30-year average by more than 100 mm (Table 2). Spring rain in 2016 was less than normal by 73 mm over May and Jun, but July through September had greater precipitation than normal (Table 2). The much later tillage and planting

Table 2 Mean monthly air temperature and precipitation for 2015 and 2016 growing seasons in Rosemount, MN as obtained from the National Centers for Environmental Information (NOAA)

Month	Air temperature[a]			Total precipitation		
	Average[b] °C	2015	2016	Average mm	2015	2016
May	20.4	19.4	21.1	103	114	69
June	25.4	24.4	26.1	120	135	81
July	27.6	26.7	29.4	114	220	121
Aug.	26.3	25.0	26.1	120	126	178
Sep.	21.8	24.4	22.8	92	126	133
Oct.	14.7	16.0	16.7	73	63	62

[a]Air temperatures shown are means of maximum daily temperatures

[b]Temperature and precipitation means shown are over a 30 year period, from 1981 to 2010

date in 2016 compared to 2015 (Table 1), which allowed an extra 13 days of growth at the time of year when kura clover growth is most rapid, contributed to dramatically more biomass at the time of tillage (Fig. 1).

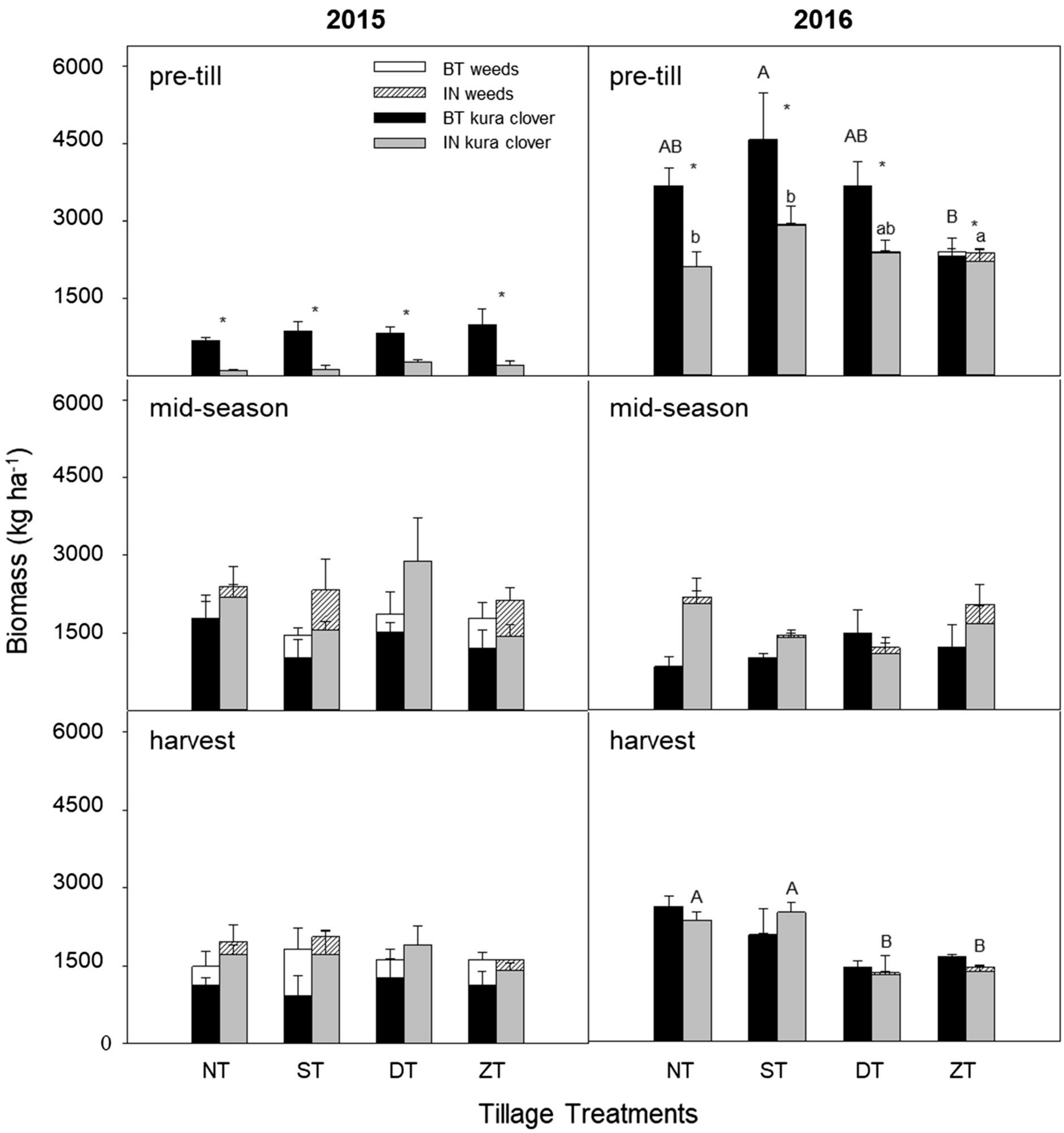

Fig. 1 Aboveground kura clover and weed biomass before spring tillage (pre-till), and the effect of tillage approach on regrowth by the middle of the growing season (mid-season), and by corn harvest (harvest) in 2015 and 2016. Error bars represent one standard error. *BT* between row, *IN* within row, *NT* no till, *ST* shank till, *ZT* zone till, *DT* double till. The same capital letters over bars within a sampling location represents no difference in kura clover biomass ($p < 0.10$). The same lowercase letters over bars within a sampling location represent no difference in weed biomass ($p < 0.10$). Asterisks (*) indicate a difference between sampling locations for kura clover biomass within a treatment at $p < 0.05$

Statistical analysis

All data were analyzed using SAS software (SAS Institute, Cary, NC). The MIXED procedure was used to determine the effects of tillage treatment (fixed) and block (random) on soil inorganic N and PMN, kura clover %N, kura clover kg biomass ha^{-1}, kura clover kg N ha^{-1}, and corn grain and stover yields. Years and sampling time points were analyzed separately due to plot relocation in 2016. A *t* test was used to compare kura clover biomass, soil inorganic N, and PMN between sampling locations (within row vs. between row). All data met the assumption of normality, but some did not have equal variance. Thus, data were subjected to Welch's ANOVA, and Satterthwaite's approximation for degrees of freedom was applied ahead of mean separations when standard deviations were not equal. To separate treatment means, probability differences of least squared means (PDIFF in LSMEANS statement; $p < 0.10$) were used. Further, in order to assess relationships between measures of yield, soil fertility, and kura clover growth and quality, Pearson's correlation coefficients were assessed by time point (Supplemental Tables 1 and 2).

Results

Biomass

Mean pre-till kura clover biomass was 518 kg ha^{-1} in 2015, when the field had been zone tilled and cropped the prior year, and approximately six times greater in 2016, when the field was undisturbed the year before, with 3035 kg ha^{-1}. Tillage treatments had no effect on kura clover and weed biomass regrowth in or between corn rows in 2015 at any time point (Fig. 1). However, in 2016, when overall greater kura clover biomass was present across the experimental treatments, the more intensive DT and ZT treatments had less kura clover biomass within corn rows at harvest than did NT and ST ($p < 0.1$; Fig. 1). Before spring tillage in both years, mean kura clover N content across all treatments ranged between 4.2% and 4.9% (Table 3). Mid-season biomass all had lower N compared to pre-till biomass, which corresponded with a greater C:N ratio.

Soil inorganic N and potentially mineralizable N

Greater rates of kura clover biomass production was associated with greater levels of soil inorganic N, as evidenced by the correlation between pre-till biomass and soil inorganic N at all three times points ($p < 0.0001$; Supplemental Table 1). After spring tillage in 2016, within row soil inorganic N was greater than between rows for ST and DT treatments (32 vs. 19, and 35 vs. 17 mg N kg soil^{-1}, respectively, $p < 0.1$; Fig. 2 and Supplemental Table 3). There was, however, no difference in available soil N in the sampled locations for the ZT treatment after tillage, although it followed a similar trend where soil within the crop row had greater soil N (31 mg N kg soil^{-1}) than between row soil (19 mg N kg soil^{-1}; Fig. 2 and Supplemental Table 3). At harvest in 2016, within row soil inorganic N was greater in DT than ST ($p < 0.1$; Fig. 2), inversely corresponding to the difference in kura clover biomass and biomass N ($p < 0.1$; Fig. 1 and Table 3, respectively) present in the crop rows at this time point.

Results showed that after tillage there was no effect of tillage treatments or location on PMN (Fig. 3). Mean PMN values trended toward being less within rows relative to between rows, but this result was not significant (Fig. 3). No correlation was found between PMN and either grain or stover yields (Supplemental Table 2).

Corn grain and stover yields

In 2015, tillage approach had no effect on corn grain or stover yields, and overall yields were low (Table 4). In 2016, grain yield was greater in ZT and DT approaches compared to NT and ST. Double till additionally had a superior stover yield in 2016 (Table 4).

As mentioned, in 2016, 68 N and 10 N sub-plot treatments were established and used only to determine effects on corn yield, not on soil N parameters. A paired *t*-test showed no yield difference between 68 N sub-plots that received organic fertilizer N prior to corn planting and 10 N sub-plots.

Table 3 Mean kura clover C:N ratio, %N, and aboveground biomass N by year, tillage treatment, and sampling location

Tillage treatment by sampling location	Pre-till			Mid-season			Harvest		
	C:N	% N	kg N ha^{-1}	C:N	% N	kg N ha^{-1}	C:N	% N	kg N ha^{-1}
2015									
In row									
NT	8.74	4.84	5.55	14.47	2.96	39.93	12.21	3.50	32.51
ST	8.75	4.74	6.91	13.43	3.20	52.06	12.17	3.48	41.88
DT	8.65	4.77	13.18	15.49	2.73	41.49	11.47	3.69	46.92
ZT	9.15	4.64	9.78	14.51	2.95	35.31	11.84	3.58	32.78
Between row									
NT	8.54	4.68	32.22	14.24	3.09	55.99	12.09	3.52	58.92
ST	8.58	4.74	41.60	13.96	3.08	56.05	11.78	3.33	57.21
DT	8.61	4.54	37.38	14.34	2.99	53.35	11.64	3.72	59.88
ZT	8.49	4.81	48.49	14.38	2.98	52.82	12.51	3.46	44.85
2016									
Within row									
NT	9.06b	4.86a	105.13	14.48	3.09	62.75	12.46	3.55	84.18a
ST	9.77ab	4.43ab	131.68	16.49	2.66	37.81	12.09	3.64	91.14a
DT	10.07ab	4.31ab	104.51	16.08	2.78	32.78	11.76	3.72	48.10b
ZT	10.41a	4.21b	94.79	16.88	2.58	41.78	11.48	3.81	51.55b
Between Row									
NT	9.67	4.54	169.00	14.50	3.07	26.09	12.67	3.45	90.12
ST	9.67	4.50	210.82	15.47	2.87	29.07	12.47	3.52	73.08
DT	9.87	4.46	166.46	15.40	2.84	41.59	12.00	3.64	52.37
ZT	9.98	4.41	104.94	15.76	2.84	32.53	11.46	3.88	63.08

Years are separated by sampling time points, and results followed by the same letter within each column are not different ($p < 0.10$)

NT no till, *ST* shank till, *ZT* zone till, *DT* double till

Discussion

Zone till approach affects kura clover contribution to soil N pools

Zone tillage approach, as well as cropping in the prior year, had an effect on the subsequent years' overall kura clover stands. Within crop rows, the more intensive DT and ZT treatments incorporated more kura clover biomass relative to NT and ST ($p < 0.1$; Fig. 1) in 2016 when overall pre-tillage stands were improved (approx. 3600 kg ha^{-1}). In that year, pre-tillage between row kura clover stands were similar to findings from two Minnesota experiments by Peterson et al. (1994) and Seguin et al. (2000), the latter of which took place at the same location as this experiment. In these studies, the first kura clover forage cutting over the course of a year averaged 3700 kg ha^{-1} and 3500 kg ha^{-1}, respectively. Additionally, between row kura clover biomass in 2016 for the three samplings totaled approx. 6700 kg ha^{-1} in this study, while Peterson et al. (1994) found that mean kura clover biomass produced over a year was 7600 kg ha^{-1}.

Lower N content in midseason biomass relative to pre-till biomass for all treatments suggests that kura clover C:N increases with legume maturation. Previous research on alfalfa has shown increasing C:N after a first cutting (Wang et al. 2015), followed by remobilization of N to shoots from roots (Ourry et al. 1994; Frank 2008). Parr et al. (2011) also showed C:N to increase over a wide range of winter annual cover crop legumes throughout spring maturation. While high C:N is generally associated with N

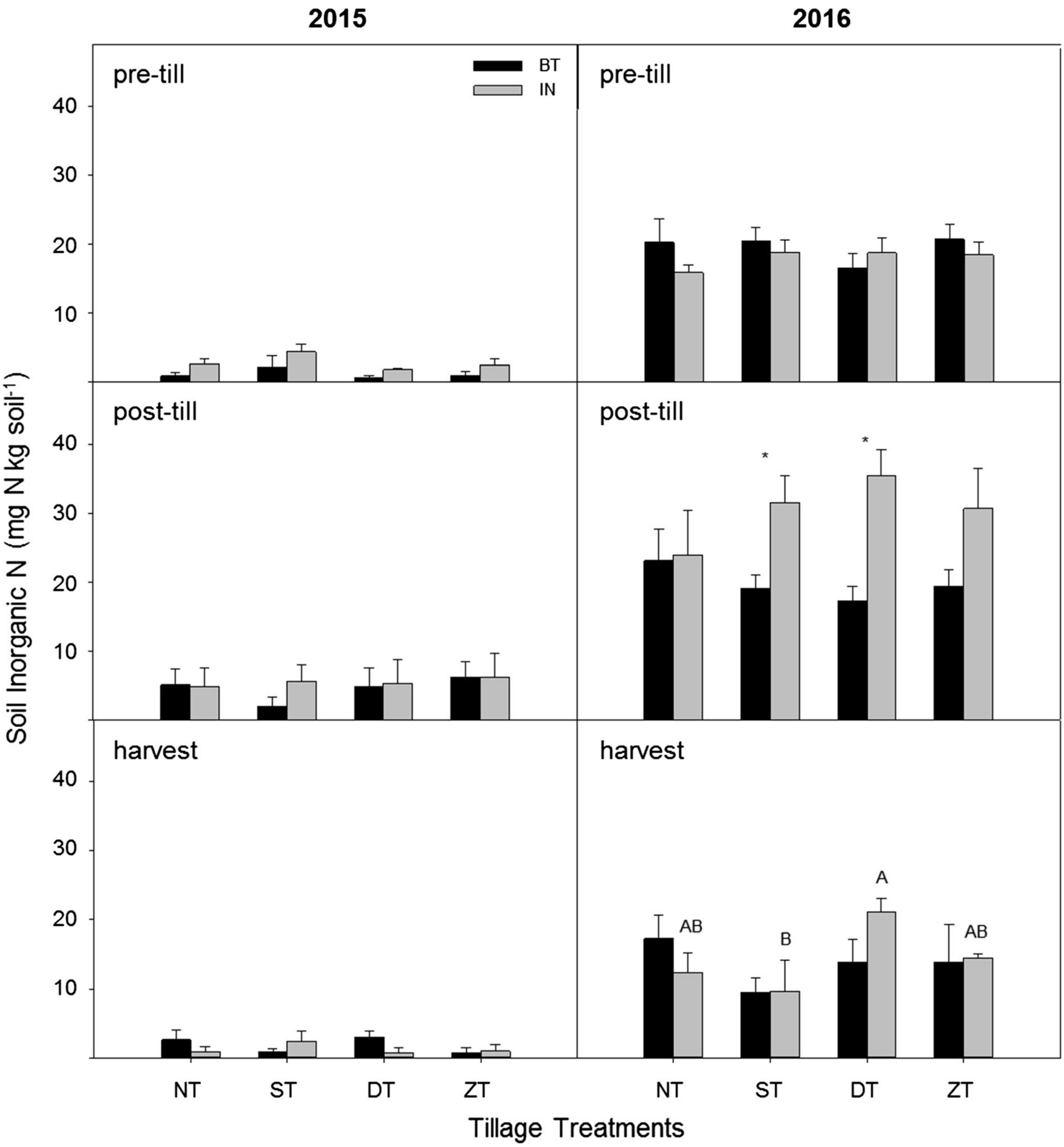

Fig. 2 Effect of tillage approach on soil inorganic nitrogen before spring tillage (pre-till), after spring tillage (post-till), and at corn harvest (harvest) in 2015 and 2016. Error bars represent one standard error. *BT* between row, *IN* within row, *NT* no till, *ST* shank till, *ZT* zone till, *DT* double till. The same letters over bars within a sampling location represents no difference in soil inorganic nitrogen ($p < 0.10$). An asterisk (*) over bars in a tillage treatment indicates a difference between sampling locations ($p < 0.10$)

immobilization, all observed C:N values were well within net mineralization ranges (less than or equal to approximately 25).

Greater soil inorganic N within rows for ST and DT approaches relative to between rows after tillage in 2016 suggests that these tillage treatments incorporated greater amounts of aboveground biomass due to

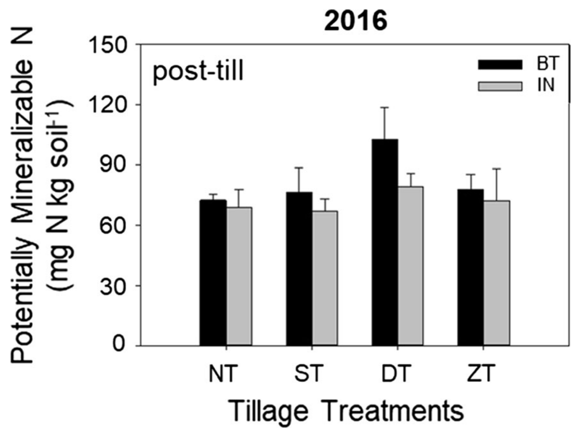

Fig. 3 Effect of tillage approach on potentially mineralizable nitrogen after spring tillage in 2016. Error bars represent one standard error. *BT* between row, *IN* within row, *NT* no till, *ST* shank till, *ZT* zone till, *DT* double till

Table 4 Mean corn grain and stover yield, 2015 and 2016

Tillage treatments	Yield			
	2015		2016	
	Grain Mg DM ha^{-1}	Stover	Grain	Stover
NT	0.61	2.11	0.17b	0.27c
ST	1.06	2.28	0.46b	0.42c
DT	1.20	2.16	3.81a	2.56a
ZT	1.00	2.05	3.00a	1.83b

Results followed by the same letter within each column are not different ($p < 0.10$)

NT no till, *ST* shank till, *ZT* zone till, *DT* double till

a wider and/or deeper disturbance area (Fig. 2). The inverse relationship at harvest between soil inorganic N and kura clover biomass, particularly for the ST approach in 2016, suggests that kura clover encroached into ST rows and decreased soil inorganic N via uptake, possibly at the expense of crop productivity (Table 2). This relationship was opposite for the DT treatment, where results suggest that within row DT kura clover could have utilized excess soil N, but that the corn crop may have limited kura clover growth via competition for sunlight or soil water instead. This is supported by greater grain and stover yields for DT than ST in 2016 (both $p < 0.0001$; Table 4).

Potentially mineralizable N was measured only in 2016 immediately following tillage, to capture the effect of tillage on organic N pools that could provide nutrient release to subsequent crops. This labile N pool has been shown to provide a longer-term source of N in organic systems as mineralization releases protected or moderately decomposed N sources (Poudel et al. 2002; McSwiney et al. 2010; Grandy et al. 2011). However, there was no effect of soil location or tillage approach on PMN, which was surprising given observed kura clover differences in quantity (Fig. 1) and quality (%N and C:N; Table 3) across tillage treatments. Additionally, there was no correlation between PMN and corn yield to support use of PMN as an agronomic predictor for corn growth (Supplemental Table 2). Mixed findings exist in the literature with respect to the relationship between PMN and inorganic soil N, and how these measures affect yield. Culman et al. (2013) found PMN was positively associated with total corn yield throughout the growing season, while soil inorganic N was only correlated to yield and corn N at the V10 growth stage. Conversely, because PMN mineralizes at varying rates, inorganic N may in fact be a better indicator of N available to crops (Overstreet and Hoyt 2008).

Zone till approach affects corn yield

Zone till approach had no effect on corn grain or stover yields in 2015, when very few ears of corn had reached maturity at harvest. Immature ears were not harvested for grain yield, thereby increasing stover yields via additional mass of immature ears. Conversely, in 2016, all harvested ears had kernels and contributed to grain yield, which was greater in ZT and DT compared to NT and ST. Double till also had greater stover yield than any other tillage treatment in 2016 (Table 4).

Results also showed that N fertility subplot treatments had no effect on corn yield. Despite this lack of an N response, overall yields observed in our organically-managed experiment were less than those in an adjacent experiment conducted using conventional management (Dobbratz et al. 2019). Differences between these organic and conventionally managed corn-kura clover systems include corn varieties used in each, as well as pre- and post-emergence glyphosate applications used in the conventional system to control weeds and reduce kura clover encroachment and water usage.

Careful control of between row cover crops in living mulch systems is critical for optimal corn yields (Affeldt et al. 2004; Ziyomo et al. 2013; Grabber et al. 2014). The kura clover at spring tillage in our study was vigorous in 2016, resulting in competition between the corn crop and encroaching kura clover growth from living strips. This encroachment was noticeable in all tillage treatments of our organic system throughout the corn season (Fig. 1). However, we observed that more disruptive treatments better displaced kura clover within crop rows by harvest (ZT and DT; Fig. 1), which positively impacted corn productivity (Table 4). This perhaps occurred because, in addition to greater levels of incorporated kura clover biomass N, these treatments also reduced competitive effects of living kura clover encroachment.

The effect of living mulch encroachment into crop rows on N provisioning and ultimately crop productivity has been studied previously, but remains a multifaceted influence. Several studies have found that competition from living mulches explains yield losses (Brandsæter et al. 1998; Sawyer et al. 2010; Grabber et al. 2014; Siller et al. 2016), while no yield loss with the use of living mulches has also been observed (Enache and Ilnicki 1990). Additionally, kura clover has been shown to have relatively low rates of biological N fixation in some Minnesota soils (Seguin et al. 2000). In living mulch systems like this one, spring zone tillage incorporates N-rich residues, resulting in greater soil N concentrations localized in the crop row. Directly, this contributes to soil N availability for the crop. However, if it encroaches into the crop row, the living mulch may utilize this soil N, decreasing N available to the crop as well as further reducing N fixation rates. This decrease in biological N fixation in the presence of high soil N environments is well-documented for many legumes (e.g. Giller and Cadisch 1995; Kai-yun et al. 2015; Saturno et al. 2017), and kura clover has been found to assimilate large quantities of soil N in its aboveground biomass (87 kg N ha^{-1}; Qi et al. 2011). In this study, it appears that a combination of high spring kura clover biomass with high intensity tillage like the DT treatment resulted in maximal N provisioning (and crop productivity), while limiting living mulch encroachment.

It is standard for conventionally-managed zone tillage systems to utilize synthetic herbicides such as glyphosate to control kura clover regrowth into crop rows (Zemenchik et al. 2000; Affeldt et al. 2004; Ochsner et al. 2010), a practice prohibited in certified organic systems. Management of organic zone tillage systems may require that OMRI approved organic herbicides are identified that can adequately control living mulch encroachment and thus reduce competitive crop effects. Preliminary evaluations on our site (unpublished data) showed promising results for such OMRI approved organic herbicides, such as 20-30% acetic acid. Further work in the field of organic weed and cover crop control could prove beneficial in the long-term adoption of living mulch systems.

Conclusions

In this study, zone tillage approaches with greater soil disturbance improved soil N status and corn yields in organic living mulch systems. When kura clover biomass production was high, systems that used the novel PTO-driven, rotary zone-till implement (ZT and DT) improved both grain and stover yields over NT and ST living mulch systems. While the exact amount of kura clover biomass incorporated by each treatment was not directly measured in this experiment, treatments with larger areas of clover incorporation were found to have greater levels of available soil N at harvest and greater corn grain yields, indicating that high-quality, leguminous plant residue at corn planting may have been responsible. Results suggest that an additional key factor was that a wider tilled zone reduced kura clover encroachment during corn germination and establishment, in turn leading to timely canopy closure that prevented kura clover competition for most of the growing season.

It should be noted that our results do not align well with NOP regulations to reduce tillage, since approaches with greater soil disturbance improved yields; however, the numerous benefits provided by living mulches and zone tillage still represent improvements from current typical row cropping practices in the Upper Midwest stemming from greater ground coverage, such as reduced soil erosion and nitrate leaching. Further, our results suggest that a year of rest prior to cropping and delayed tillage and planting, as was practiced in the 2nd year of our study, can markedly increase kura clover biomass production and N contributions. This practice allows for decreased tillage, as well as the additional benefit of increased profitability for growers who choose to harvest the kura clover for forage.

Additional work in this area should concentrate on quantifying the proportion of within row kura clover shoot material incorporated through various zone till approaches, and more frequent within row soil sampling for inorganic N and PMN. Finally, work to create an implement for between row mowing of the kura clover biomass and depositing it into rows would be highly valuable for more precisely localizing mineralized plant nutrients throughout the growing season, rather than only at planting.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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