Response of Continuous Maize with Stover Removal to Living Mulches

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Biofuels

ABSTRACT

Constraints to maize (*Zea mays* L.) stover biomass harvest may be mitigated by using a living mulch (LM) to offset C exports and control soil erosion. Living mulches can compete with the main crop for resources. The objective of this research was to quantify competitive effects of LM management systems grown in continuous maize with stover removal. Maize was planted into creeping red fescue (CF) (*Festuca rubra* L.), Kentucky bluegrass (KB) (*Poa pratensis* L.), and a mixture of CF and white clover (*Trifolium repens* L.) (MX) LMs in 2008, 2009, and 2010 near Ames, IA. Management treatments were fall strip-tillage (ST) and no-tillage (NT), with either a pre-planting paraquat burn-down followed by two glyphosate bands (PQ) or glyphosate bands only (GLY). Kentucky bluegrass PQ ST produced similar grain yields (11,230 kg ha^{-1}) all 3 yr as the no LM control (11,810 kg ha^{-1}) with a harvest index (HI) of 0.55 compared to 0.52 in the control, averaged across years. The control produced greater stover dry matter (SDM) (10,110 kg ha^{-1}) 2 of the 3 yr compared to KB PQ ST (8600 kg ha^{-1}). Total groundcover averaged 80% in KB PQ ST compared to only 45% in the no LM control. These results indicate that a combination of herbicide suppression and ST suppresses LMs adequately to maintain competitive maize grain yields. Additional research under varying climatic conditions will further quantify the risk of LM management systems to increase the sustainable stover harvest of maize biomass feedstocks.

Harvesting agricultural crop residues as biomass feedstocks could contribute between 27 and 180 million dry tonnes annually between 2012 and 2030 toward U.S. biofuel production (USDE, 2011). The range in these estimates accounts for variability in price per dry tonne using baseline assumptions. Maize stover represents approximately 80% of this dry biomass. Continual removal of >25% of maize stover decreases soil productivity by lowering soil organic carbon (SOC) and removal effects on maize yield may be enhanced by soil type and topography (Blanco-Canqui and Lal, 2007). Doran et al. (1984) also reported lower maize yields when complete residue removal occurred but little or no effect on maize yield with 50% removal. In contrast, Coulter and Nafziger (2008) reported that residue removal from productive soils in years with adequate rainfall has the potential to increase maize grain yields and lower N fertilizer requirements in the short-term. Wilhelm et al. (2007) estimated that leaving 5.25 Mg stover ha^{-1} yr^{-1} is required to maintain SOC in NT or conservation tillage in continuous maize compared to 7.58 Mg stover ha^{-1} yr^{-1} in a moldboard plow tillage system. These estimates to maintain SOC are significantly higher than estimates to maintain soil erosion within the accepted tolerance (Wilhelm et al., 2007).

Innovative cropping system design may offer solutions to current constraints on sustainable biomass feedstock availability. Incorporating LMs into maize production systems can supply C to offset C harvested in stover, among other benefits. Living mulches have been used in maize-based cropping systems to supply forage, suppress weeds, and supply N (Elkins et al., 1979; Eberlein et al., 1992; Zemenchik et al., 2000; Singer et al., 2009). In continuous maize systems, a C3 LM species would be a logical functional group choice. A C3 species would exhibit dominant spring growth, which would reduce the competitive potential of the LM during the dominant summer growth period of the C4 species. Elkins et al. (1979) concluded it was possible to obtain good maize yields in chemically suppressed KB or tall fescue (*F. arundinacea* Schreb.), while maintaining at least 50% of the grass sod. Eberlein et al. (1992) reported lower non-irrigated maize yields in a partially suppressed alfalfa (*Medicago sativa* L.) LM compared to a no LM control and concluded that LM systems in the Upper Midwest may be too risky without irrigation.

Living mulch cropping systems introduce the potential for higher risk of main crop yield reductions because different species are growing concurrently. Selecting contrasting functional groups with LM suppression management can mitigate potentially negative competitive effects. Furthermore, the presence of the LM on the soil surface may provide positive soil water effects late in the growing season when the maize crop relies on rainfall after stored soil water is depleted. A shaded LM minimally transpires, lowers soil water evaporation (Ochsner et al.,

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Abbreviations: BSN, basal stalk nitrate; CF, creeping red fescue; DM, dry matter; HI, harvest index; KB, Kentucky bluegrass; GLY, glyphosate band; GRND, groundcover; LM, living mulch; LMK, living mulch potassium uptake; LMN, living mulch nitrogen uptake; LMP, living mulch phosphorus uptake; MX, mixture of CF and white clover; NT, no-tillage; PQ, pre-planting paraquat burn-down followed by two glyphosate bands; SDM, stover dry matter; SN, stover nitrogen uptake; SOC, soil organic carbon; SP, stover phosphorus uptake; ST, strip-tillage; TKW, 1000-kernel weight; UAN, urea ammonium nitrate.

2010), and likely increases water infiltration compared to bare soil. Wiggans et al. (2012) reported that a KB LM increased maize reproductive water use efficiency compared to a no LM control during 2 of 3 yr. The objectives of this research were to quantify agronomic responses of maize growing in LMs to understand competitive effects on maize grain yield and yield components. Treatments were selected that provided varying levels of competition/suppression of the LM to quantify maize whole-plant response during three production seasons.

MATERIALS AND METHODS

Field research was conducted in 2008, 2009, and 2010 on the Iowa State University Agronomy and Agricultural Engineering Sorenson Research Farm near Ames, IA (42° N, 93°46' W) on a Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soil. The research area was previously in a maize–soybean [*Glycine max* (L.) Merr.] rotation. Soybean was mowed with a rotary cutter on 25 July 2006. Plots were disked 31 July 2006 and 8 Aug. 2006, then field cultivated on 15 Aug. 2006. Living mulch species were drilled 21 Aug. 2006 in 10 20-cm wide rows with double disk openers and 5-cm wide press wheels and rolled with a 2.1-m wide pulverizer/packer. 'Troy' KB and CF (variety not stated) were seeded at 49 and 56 kg ha^{-1} and the white clover + CF mixture was seeded at a combined rate of 2 and 28 kg ha^{-1}, respectively. Maize was planted 14 May 2007 in five 0.76 m rows at 81,510 seeds ha^{-1} to establish a maize history. Soil test levels in the surface 20 cm measured 21.8 mg kg^{-1} P and 156 mg kg^{-1} K using Mehlich 3 for both elements, 6.6 pH, and 48 g kg^{-1} organic matter in 2006.

The experimental design was an unbalanced randomized complete block in a split-plot treatment arrangement with four replicates. Whole plots, 15.2 m wide by 22.9 m long, consisted of three LM treatments, CF, KB, and MX and a no LM control. Control plots were only 3.8 m wide by 22.9 m long. Subplots, 3.8 m wide (five-rows) by 22.9 m long, included fall ST with glyphosate bands over the row (GLY ST), fall ST with a pre-emergent paraquat (PQ) burndown and glyphosate banded over the row (PQ ST), NT with glyphosate banded over the row (GLY NT), and NT with a pre-emergent PQ burndown and glyphosate banded over the row (PQ NT). This treatment arrangement was a 2 × 2 factorial. Control plots were managed using NT and maintained weed free with glyphosate. Glyphosate [N- (phosphonomethyl) glycine] (Roundup WeatherMAX, Monsanto, St. Louis, MO) was applied at a rate of 1.0 kg a.i. ha^{-1} in a 25 cm band directly over the existing maize row. Paraquat dichloride [1,1'-dimethyl-4,4'-bipyridinium dichloride] (Gramoxone Inteon, Syngenta Crop Protection, Inc., Greensboro, NC) was broadcast over the plot at a rate of 0.84 kg a.i. ha^{-1}. Glyphosate was applied twice in the PQ treatments and three times in the GLY treatments each season. Paraquat applications occurred within a few days before maize planting or within a few days after planting. The first glyphosate application occurred approximately the same time as the paraquat application in the GLY treatment and all plots received two additional glyphosate applications at approximately 2-wk intervals after these first herbicide applications. The last glyphosate application occurred at approximately the V6–V7 growth stage (Ritchie et al., 1996) each year.

Strip-tillage was performed in November using a five-row implement containing 50 cm diam. smooth coulters operating directly in front of 43 cm long mounted shanks. The terminal points of the shanks were 4.5 cm wide mole knives. A pair of 40-cm notched sealer disks followed behind the mole knives, performing a minor hilling effect to the disturbed soil. The resulting ST zone for each row was 25 cm wide, 20- to 25-cm deep, and displayed a variable soil mound of 0 to 10 cm in height. Pioneer Brand 34A20 was planted on 16 May 2008, 5 May 2009, and 29 Apr. 2010 at 86,450 seeds ha^{-1} in five 0.76 m rows in the same plots all years and in the same row location as previous years at a target seeding depth of 5 cm. A five-row planter was used with row cleaners. This hybrid was adapted to this location and contained biotech traits for herbicide tolerance and insect resistance. A point-injector applicator was used to sidedress 202, 168, and 168 kg N as urea ammonium nitrate (UAN) on 19 June 2008, 4 June 2009, and 1 June 2010, which corresponded approximately to the V4 to V6 growth stage each year. In 2009 and 2010, an additional 39 kg of UAN was applied at planting with a planter-disk opener approximately 5-cm deep and 5 cm offset from the row. The point injector applicator is described in more detail in Baker et al. (1989). Soil fertility amendments were applied in November each year by applying diammonium phosphate + potash 18-cm deep at a rate of 19–39–223 (N–P–K) kg ha^{-1} with a coulter-knife injector in the row to ensure nutrient sufficiency.

Maize phenology was determined in all subplots from emergence to maturity using procedures by Ritchie et al. (1996). Six plants per subplot were marked and staged weekly to determine growth stage. Weed density and composition were determined in each subplot (excluding the control) at R2 in a 0.76 m^2 area. Maize harvest plant population was determined at R6 in each subplot by counting all plants in 7.6 m of the three middle rows. Percent total groundcover (GRND) was determined by taking two digital photographs at an approximate height of 1.4 m in each subplot following ST. Taking images at this height provided an approximate 1.0 m^2 area across a single row. In 2008, no digital photographs were taken in the control plots. Each photograph was placed on a 100-point grid to estimate percent GRND.

At R6, maize aboveground dry matter (DM) was sampled from 1.0 m^2 above the brace roots in each subplot. Grain was separated from the stover to determine grain yield, HI, 1000-kernel weight (TKW), kernel number, and total N grain content. Harvest index was calculated as the ratio of dry grain weight to total shoot dry weight. Grain yield was adjusted to 155 g kg^{-1} moisture content. Grain mass for TKW is presented on a DM basis (American Society of Agricultural and Biological Engineering, 1988). After collecting the R6 sample, a self-propelled silage chopper was used to remove shoot DM leaving approximately an 8-cm stubble height.

A 50-mg grain subsample was ground (Bosch Nutrimill Grain Mill) to pass through a 1-mm screen and analyzed for total N content using flash combustion and a thermal conductivity detector on a gas chromatograph column. Stover was dried in a forced-air oven at 70°C until constant weight to determine DM, then hammer-milled. A subsample was collected and ground to pass through a 1-mm screen using a Thomas Model 4 Wiley mill (Thomas Scientific, Swedesboro, NJ) and a direct-drive cyclone sample mill (Model 3010-014, UDY Corporation, Fort Collins, CO) to be analyzed for total N, P, and K content. Total N content was measured as previously described. Phosphorus and K were analyzed using an inductively coupled plasma–optical emission spectrometer (ICP–OES) after wet acid tissue digestion with 3 mL H_2SO_4 and dilution to 50 mL using deionized water. Maize grain and stover total N, P, and K uptake were calculated as the product of shoot N, P, and K concentration and shoot DM.

Maize stalk segments were collected for basal stalk nitrate (BSN, NO_3–N) determination from the shoot sample at harvest. Stalk segments 0.20 m in length were collected 0.15 m above the soil surface in each subplot, dried at 60°C for 5 d, ground to pass through a 1-mm screen, and analyzed for NO_3–N by leaching 0.25 g of ground sample with 50 mL of 2 M KCL solution, creating a 200-fold dilution. Nitrate concentration in the leachate was determined using a Lachat autoanalyzer (Lachat Instruments, Milwaukee, WI; Method 12-107-04-1-B). Other than the 0.25-g sample for this analysis, the remaining stalk segment DM was added back to the R6 shoot DM sample.

Living mulch shoot DM was collected in October each year. All LM shoot material was clipped at the soil surface in two 0.38 m^2 (0.76 m wide by 0.5 m long) quadrats that straddled a single row and composited in all LM subplots. Shoot DM was dried at 70°C until constant weight and ground to pass through a 1-mm screen using a Thomas Model 4 Wiley mill (Thomas Scientific, Swedesboro, NJ) and a direct-drive cyclone sample mill before analysis for total N, P, and K content. Samples were analyzed following the same methodology as previously described. Living mulch shoot N, P, and K uptake were calculated as the product of shoot N, P, and K concentration and shoot DM. Daily rainfall and mean air temperature were downloaded from the Iowa Environmental Mesonet NWS COOP 8WSW weather station located approximately 2 km from the research site.

Data were analyzed using PROC MIXED in SAS Version 9.2 (SAS Institute, 2008). Before analysis all data were checked to verify assumptions for independence and normality. No transformations were required for these data sets. Data were initially evaluated for independence and year effects by analyzing the data as a split-plot in time. Years were highly significant and were subsequently presented separately. Due to the unbalanced design, data were analyzed using two approaches. First, treatments were analyzed as a standard split-plot with LM, tillage, and herbicide as fixed effects and block as a random effect. Degrees of freedom were adjusted using the Satterthwaite approximation and P values were adjusted using Tukey's probability adjustments (pdiff command). This analysis evaluated all main and interaction effects but did not compare the treatments to the control. As a first analysis it allowed main and interaction effects to be tested easily. Because the design was unbalanced due to the control plots randomized as whole-plots vs. being replicated within each LM at the subplot level, a second analysis was performed to compare the control to all treatment combinations. All herbicide and tillage treatments were assigned specific identities within a LM species. For example, Treatment 1 consisted of PQ NT and Treatment 2 was PQ ST. Assigning specific identities to each treatment factor (NT = 1, ST = 1, PQ = 2, and GLY = 2) allowed data to be compared to the control as a one-way mixed model. A similar unbalanced design experiment was analyzed using the same approach in Singer et al. (2011). Block again was considered a random effect and treatments were considered fixed effects. Degrees of freedom were adjusted using Satterthwaite approximation, P values were adjusted using Tukey's probability adjustments, and effects were considered significant if main effects or interaction p values were ≤0.05. The second model was only used for the variables that included the no LM control plots. Measurements including LM DM, LM N uptake, LM P uptake, LM K uptake, weed density, and GRND in 2008 were not analyzed using the second model.

RESULTS AND DISCUSSION

Grain Yield

Living mulch ($p = 0.007$), herbicide ($p = 0.001$), tillage × herbicide ($p = 0.013$), and the LM × treatment interaction ($p < 0.001$) significantly affected maize yield in 2008, although tillage was not significant ($p = 0.910$). In 2009, herbicide was significant for grain yield ($p < 0.001$) and the LM × treatment interaction ($p = 0.039$). In 2010, grain yield was affected by LM ($p = 0.014$), tillage, ($p = 0.003$), herbicide ($p < 0.001$), and the LM × treatment interaction ($p < 0.001$). Above average winter snowfall and early season rainfall in 2008 delayed maize planting and herbicide treatments for 2 to 3 wk (Table 1) and this contributed to more marked treatment separation because the LMs were more competitive. Among living mulch species, KB had greater maize yield than CF or MX, while MX and CF were similar (Table 2). Averaged across LM, PQ ST (8740 kg ha^{-1}) yielded higher than PQ NT (7830 kg ha^{-1}), and GLY NT (7490 kg ha^{-1}) was greater than GLY ST (6500 kg ha^{-1}). In 2008, grain yields ranged from 5620 (MX GLY ST) to 13,070 (No LM control) kg ha^{-1}. Compared to the no LM control, grain yield was significantly lower in all treatments except KB PQ ST in 2008.

In 2009, maize grain yields ranged from 7610 kg ha^{-1} (CF GLY NT) to 12,770 kg ha^{-1} (KB PQ NT)(Table 3). Averaged across groundcover and tillage, PQ (12,070 kg ha^{-1}) yielded greater than GLY (9880 kg ha^{-1}). Only CF GLY NT was significantly lower than the control in 2009. The lack of differences in 2009 may be attributed to more normal growing season rainfall, particularly during May and June that allowed for timely herbicide applications. These results support findings by Hall et al. (1984), who conducted LM research in

Table 1. Average monthly air temperature and precipitation collected approximately 2 km from the experimental site†. Thirty-year averages were computed from data collected between 1975 and 2004.

	Air temperature				Precipitation			
Month	2008	2009	2010	30-yr	2008	2009	2010	30-yr
	°C				mm			
Mar.	1.0	3.8	4.0	2.8	71	103	38	53
Apr.	8.4	9.2	13.0	10.3	130	116	100	93
May	15.2	16.0	15.9	16.5	216	104	89	112
June	21.2	20.8	21.8	21.4	271	104	312	119
July	23.2	20.5	23.9	23.5	234	70	122	112
Aug.	21.5	20.9	23.8	22.1	53	123	396	120
Sept.	17.9	18.1	17.5	18.1	78	24	126	76
Oct.	11.6	7.9	13.3	11.1	92	186	12	61
Nov.	3.1	7.0	4.0	2.6	66	34	58	51

† NWS COOP site Ames 8WSW.

Table 2. Treatment means and probability values for living mulch, tillage, and herbicide for grain yield (GY), kernel number (KN), 1000-kernel weight (TKW), harvest index (HI), grain nitrogen uptake (GNU), and plant density (PD) in 2008 near Ames, IA.

Treatment	GY	KN	TKW	HI	GNU	PD
	kg ha^{-1}	no. m^{-2}	g		kg ha^{-1}	plants ha^{-1}
Control (C)	13,070	4297	259	0.56	122	87,080
CF PQ NT†	6,260	2138	249	0.56	61	85,410
CF PQ ST	7,410	2654	238	0.56	70	82,540
CF GLY NT	6,380	2197	247	0.58	64	80,620
CF GLY ST	5,980	2074	246	0.59	59	80,620
KB PQ NT	9,250	3210	246	0.57	88	88,760
KB PQ ST	11,340	3934	245	0.59	104	82,060
KB GLY NT	8,880	3028	250	0.58	86	82,780
KB GLY ST	7,910	2722	247	0.57	75	78,470
MX PQ NT	7,980	2692	252	0.58	75	84,450
MX PQ ST	7,460	2587	245	0.57	70	79,190
MX GLY NT	7,220	2514	247	0.55	68	77,510
MX GLY ST	5,620	1762	277	0.54	57	74,640
			$P > t$			
CF vs. KB	0.007	0.010	0.955	0.887	0.009	0.949
CF vs. MX	0.642	0.840	0.389	0.540	0.751	0.385
KB vs. MX	0.021	0.019	0.530	0.321	0.020	0.267
PQ vs. GLY	0.001	<0.001	0.066	0.783	0.005	0.005
NT vs. ST	0.910	0.951	0.682	1.000	0.718	0.024
C vs. CF PQ NT	<0.001	<0.001	0.331	1.000	<0.001	0.664
C vs. CF PQ ST	<0.001	<0.001	0.051	1.000	<0.001	0.243
C vs. KB PQ NT	<0.001	0.002	0.212	0.724	<0.001	0.664
C vs. KB PQ ST	0.081	0.278	0.197	0.201	0.062	0.198
CF PQ NT vs. CF PQ ST	0.197	0.097	0.204	1.000	0.328	0.437
KB PQ NT vs. KB PQ ST	0.023	0.022	0.954	0.358	0.061	0.076

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

Table 3. Treatment means and probability values for living mulch, tillage, and herbicide for grain yield (GY), kernel number (KN), 1000-kernel weight (TKW), harvest index (HI), grain nitrogen uptake (GNU), and plant density (PD) in 2009 near Ames, IA.

Treatment	GY	KN	TKW	HI	GNU	PD
	kg ha^{-1}	no. m^{-2}	g		kg ha^{-1}	plants ha^{-1}
Control (C)	11,690	4127	245	0.47	128	82,140
CF PQ NT†	11,360	3984	244	0.48	61	81,910
CF PQ ST	12,260	4067	257	0.50	75	80,950
CF GLY NT	7,610	2638	246	0.45	66	83,100
CF GLY ST	10,410	3628	243	0.50	56	78,570
KB PQ NT	12,770	4179	261	0.50	93	78,570
KB PQ ST	12,320	4375	240	0.51	119	81,190
KB GLY NT	10,520	3659	245	0.49	81	84,760
KB GLY ST	10,400	3662	245	0.50	79	81,670
MX PQ NT	12,030	3891	263	0.50	73	84,290
MX PQ ST	11,660	3720	267	0.49	77	80,950
MX GLY NT	10,110	3318	259	0.48	69	81,670
MX GLY ST	10,270	3257	273	0.48	56	80,240
			$P > t$			
CF vs. KB	0.257	0.106	0.999	0.142	0.002	0.975
CF vs. MX	0.616	0.988	0.113	0.804	0.700	0.939
KB vs. MX	0.721	0.088	0.114	0.316	0.005	0.991
PQ vs. GLY	<0.001	<0.001	0.511	0.188	<0.001	0.748
NT vs. ST	0.313	0.310	0.808	0.129	0.403	0.117
C vs. CF PQ NT	0.684	0.669	0.937	0.783	<0.001	0.936
C vs. CF PQ ST	0.750	0.885	0.349	0.137	<0.001	0.689
C vs. KB PQ NT	0.469	0.900	0.237	0.080	0.001	0.235
C vs. KB PQ ST	0.716	0.551	0.702	0.060	0.284	0.749
CF PQ NT vs. CF PQ ST	0.459	0.788	0.298	0.242	0.102	0.723
KB PQ NT vs. KB PQ ST	0.709	0.656	0.113	0.895	0.002	0.333

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

Pennsylvania and concluded LMs did not significantly affect grain yield if properly suppressed with herbicide treatments.

In 2010, grain yields ranged from 3450 (MX GLY NT) to 10,680 (No LM control) kg ha^{-1} (Table 4). Averaged across tillage and herbicide, KB yielded 7250 kg ha^{-1} compared to 6660 and 5460 kg ha^{-1} in CF and MX. Averaged across LM and herbicide, ST yielded 7080 kg ha^{-1} compared to 5830 kg ha^{-1} in NT. Averaged across LM and tillage, PQ yielded 8150 kg ha^{-1} compared to 4770 kg ha^{-1} in GLY. In 2010, only KB PQ ST and CF PQ ST produced yields that were not different than the control. The control reached 50% silking 75, 78, and 76 d after planting in 2008, 2009, and 2010 compared to 80, 80, and 76 d after planting in KB PQ ST and was only significantly different than KB PQ ST in 2008 (data not presented).

Across the three study years, herbicide treatment had the most consistent effect on maize grain yield. Clearly, GLY alone does not provide sufficient LM suppression to maintain consistently high yields. The GLY treatment was included in this experiment because of the C contribution from the LMs. Carbon inputs and exports will be presented in a separate manuscript. Tillage had a pronounced effect in 2008 and 2010, years with above normal rainfall. In 2008, rainfall was 40, 93, 128, and 209% above average in April, May, June, and July. In 2010, June and August rainfall were 262 and 330% above normal. Kovar et al. (2011) reported that an interrow knife injected manure treatment increased rainfall required to produce runoff by 94% compared to a no-till control in the fall. In the spring the same comparison was 62%, although it was not statistically significant. Cassel and Wagger (1996) reported that cumulative infiltration without irrigation in an untrafficked interrow was increased using fall chisel tillage (22-cm depth) by 60 and 138% each year of a 2-yr study compared with no-till. In the present study, the fall strip-till treatment tilled a narrow band over the future row to approximately a 20–25 cm soil depth, which likely enhanced infiltration, drainage, and aerobic rhizosphere conditions for maize root growth compared to no-till. Kentucky bluegrass PQ ST produced yields not different than the control in all three study years and exhibits the most potential to scale-up this production system for future experimentation. Nevertheless, CF PQ ST also produced similar yields as the control in 2 of the 3 yr but likely increases the risk of competitive effects if suppression does not occur in a timely fashion. This was exhibited in 2008 when wet field conditions prevented timely suppression and CF PQ ST produced more than double the biomass as the KB PQ ST treatment.

Kernel Number

Kernel number responses followed grain yield responses all 3 yr. In 2008, LM ($p = 0.008$), herbicide ($p < 0.001$), tillage × herbicide interaction ($p = 0.004$), and the LM × treatment interaction were significant ($p < 0.001$). Herbicide ($p < 0.001$) and the LM × treatment interaction ($p = 0.041$) were significant in 2009. In 2010, LM ($p = 0.006$), tillage ($p = 0.011$), herbicide

Table 4. Treatment means and probability values for living mulch, tillage, and herbicide for grain yield (GY), kernel number (KN), 1000-kernel weight (TKW), harvest index (HI), grain nitrogen uptake (GNU), and plant density (PD) in 2010 near Ames, IA.

Treatment	GY	KN	TKW	HI	GNU	PD
	kg ha^{-1}	no. m^{-2}	g		kg ha^{-1}	plants ha^{-1}
Control (C)	10,680	4398	243	0.52	138	78,330
CF PQ NT†	7,340	3158	231	0.54	93	74,520
CF PQ ST	9,970	4053	246	0.54	122	80,480
CF GLY NT	3,890	1880	214	0.52	53	70,480
CF GLY ST	5,430	2406	226	0.55	74	68,570
KB PQ NT	7,720	3374	228	0.51	94	71,670
KB PQ ST	10,030	4287	234	0.54	125	74,760
KB GLY NT	5,470	2593	211	0.53	67	71,910
KB GLY ST	5,760	2647	218	0.50	70	73,570
MX PQ NT	7,100	3090	232	0.53	89	71,670
MX PQ ST	6,720	2966	224	0.53	79	74,520
MX GLY NT	3,450	1495	229	0.51	45	67,620
MX GLY ST	4,590	2095	220	0.51	60	67,140
			$P > t$			
CF vs. KB	0.398	0.145	0.665	0.432	0.779	0.947
CF vs. MX	0.067	0.059	0.909	0.575	0.028	0.212
KB vs. MX	0.013	0.005	0.886	0.959	0.013	0.313
PQ vs. GLY	<0.001	<0.001	0.004	0.244	<0.001	0.012
NT vs. ST	0.003	0.011	0.326	0.486	0.004	0.296
C vs. CF PQ NT	<0.001	0.002	0.326	0.356	<0.001	0.341
C vs. CF PQ ST	0.435	0.376	0.754	0.236	0.138	0.590
C vs. KB PQ NT	0.002	0.011	0.198	0.788	<0.001	0.100
C vs. KB PQ ST	0.475	0.775	0.426	0.372	0.228	0.371
CF PQ NT vs. CF PQ ST	0.007	0.036	0.143	0.783	0.018	0.162
KB PQ NT vs. KB PQ ST	0.017	0.033	0.563	0.236	0.011	0.461

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

($p < 0.001$), and the LM × treatment interaction ($p < 0.001$) were significant. In 2008, PQ ST (3058 kernels m^{-2}) produced greater kernel number followed by PQ NT (2680 kernels m^{-2}), GLY NT (2579 kernels m^{-2}), and GLY ST (2186 kernels m^{-2})(Table 2). In 2009, PQ (4030 kernels m^{-2}) produced greater kernel number than GLY (3360 kernels m^{-2}), averaged across LM and tillage (Table 3). In 2010, averaged across tillage and herbicide, KB, CF, and MX produced 3225, 2874, and 2411 kernels m^{-2} (Table 4). Averaged across LM and herbicide, ST produced 3076 kernels m^{-2} compared to 2598 kernels m^{-2} in NT. Averaged across LM and tillage, PQ produced 3488 kernels m^{-2} compared to 2186 kernels m^{-2} in GLY. Compared to the control, kernel number was significantly lower in all treatments except KB PQ ST ($p = 0.278$) in 2008. Only CF GLY NT and MX GLY ST were significant lower than the control in 2009. In 2010, similar to grain yield results, KB PQ ST and CF PQ ST produced kernel number not different than the control. Kernel number reductions in the wet years 2008 and 2010 in NT treatments are corroborated by Cox et al. (1990), who reported 29% lower kernel number in maize in an undrained no-till treatment compared to a no-till drained treatment in a wet year with 74 and 93% higher rainfall than the 30-yr average in June and July.

Kernel Weight

In 2008, herbicide was not significant ($p = 0.066$), the tillage × herbicide interaction was significant ($p = 0.035$), and the LM × treatment interaction was not significant ($p = 0.067$). There were no significant main effects or interactions for TKW in 2009 at the $\alpha = 0.05$ probability level, although LM was moderately significant ($p = 0.082$). In 2010, herbicide was the only significant variable ($p = 0.004$). In 2008, CF GLY ST produced the greatest TKW (277 g), but also produced the lowest grain yield (Table 2). Averaged across LM, GLY ST (257) > PQ NT (249) = GLY NT (248) > PQ ST (243). In 2009, TKW of the control treatment was 245 g, with an average weight of 253 g across all treatments (Table 3). In 2010 averaged across LM and tillage, TKW in PQ treatments was 233 g compared to 220 g in GLY (Table 4). Among LM treatments, higher TKW did not increase grain yield in any year. In 2009 when KB PQ ST yielded 12,320 kg ha^{-1} compared to the control yield of 11,690 kg ha^{-1}, TKW in KB PQ ST was 240 g compared to 245 g in the no LM control. In contrast, kernel number was 4375 kernels m^{-2} in KB PQ ST compared to 4127 kernels m^{-2} in the control. Yield components were affected more by changes in kernel number than changes in kernel weight, regardless of the abiotic environment during sink establishment. Previous reports indicate kernel number is lowered by water deficit more from 2 to 7 d after after silking and continuing until 16 to 22 d after silking (Grant et al., 1989). These authors also reported reductions in kernel weight during the grain-filling period, with the lowest kernel weight occurring for stress between 12 and 16 d after silking. Maize plants growing during this period in 2009 in this study were subject to water stress (Wiggans et al., 2012) and supports these previous findings of lower kernel number and kernel weight.

Harvest Index

In 2008, only the LM × herbicide interaction was significant ($p = 0.032$). No significant main effects or interactions occurred in 2009 or 2010. In 2008 averaged across tillage, only MX GLY HI was lower than MX PQ. Harvest index values in 2008 were higher than normal because of hail damage that occurred around pollination and damaged and subsequently decreased stover DM. Harvest index in 2009 averaged across treatments was 0.49. The control HI was 0.56 in 2008, 0.47 in 2009, and 0.52 in 2010 (Tables 2–4). No treatments were significantly different compared to the control any year.

Grain Nitrogen Uptake

In 2008 and 2009, LM ($p = 0.008$ and $p = 0.002$), herbicide ($p = 0.005$ and $p < 0.001$), tillage × herbicide ($p = 0.029$ and $p = 0.001$), and the LM × treatment interaction ($p < 0.001$ and $p < 0.001$) were significant. In 2010, LM ($p = 0.011$), tillage ($p = 0.004$), herbicide ($p < 0.001$), and the LM × treatment interaction ($p < 0.001$) were significant. In 2008 and 2009, PQ ST (81 and 90 kg ha^{-1}) accumulated the greatest N, followed by PQ NT (75 and 76 kg ha^{-1}), GLY NT (73 and 72 kg ha^{-1}), and GLY ST (64 and 63 kg ha^{-1})(Tables 2 and 3). The only nonsignificant LM × treatment comparison occurred between the control and KB PQ ST, which accumulated 104 and 119 kg N ha^{-1} in 2008 and 2009 (Tables 3 and 4). In 2010, grain N uptake in CF PQ ST and KB PQ ST were not different than the control and had similar grain yields as the control. Treatments accumulating the greatest grain N produced the highest yields in each of the wet years (2008 and 2010), but this pattern did not hold for 2009. In 2009,

Table 5. Treatment means and probability values for living mulch species, tillage, and herbicide for stover (S) dry matter (DM), N, P, and K uptake, and basal stalk nitrate concentration (BSN) in 2008 near Ames, IA.

Treatment	SDM	SN	SP	SK	BSN
	kg ha^{-1}				mg NO_3–N kg^{-1}
Control (C)	8,780	60	2.8	74	248
CF PQ NT†	4,250	34	4.4	49	313
CF PQ ST	4,920	40	4.0	59	695
CF GLY NT	3,920	30	3.6	49	720
CF GLY ST	3,580	29	3.2	43	1272
KB PQ NT	6,050	45	5.2	66	541
KB PQ ST	6,880	46	3.9	78	634
KB GLY NT	5,440	36	4.8	62	281
KB GLY ST	5,030	39	4.7	60	686
MX PQ NT	4,880	38	4.8	63	544
MX PQ ST	4,660	36	3.9	57	591
MX GLY NT	5,120	37	5.9	61	624
MX GLY ST	4,220	35	6.2	51	638
	$P > t$				
CF vs. KB	0.001	0.003	0.570	0.002	0.694
CF vs. MX	0.152	0.123	0.269	0.062	0.830
KB vs. MX	0.010	0.037	0.787	0.054	0.966
PQ vs. GLY	<0.001	0.002	0.361	<0.001	0.236
NT vs. ST	0.752	0.600	0.240	0.863	0.056
C vs. CF PQ NT	<0.001	<0.001	0.192	<0.001	0.854
C vs. CF PQ ST	<0.001	<0.001	0.351	0.008	0.213
C vs. KB PQ NT	<0.001	<0.001	0.063	0.145	0.410
C vs. KB PQ ST	<0.001	<0.001	0.395	0.467	0.280
CF PQ NT vs. CF PQ ST	0.127	0.144	0.631	0.088	0.212
KB PQ NT vs. KB PQ ST	0.064	0.795	0.190	0.029	0.757

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

Table 6. Treatment means and probability values for living mulch species, tillage, and herbicide for stover (S) dry matter (DM), N, P, and K uptake, and basal stalk nitrate concentration (BSN) in 2009 near Ames, IA.

Treatment	SDM	SN	SP	SK	BSN
	kg ha^{-1}				mg NO_3–N kg^{-1}
Control (C)	11,520	77	6.8	98	1008
CF PQ NT†	10,500	92	9.6	106	1847
CF PQ ST	10,630	83	7.9	116	2021
CF GLY NT	7,900	81	9.4	84	1587
CF GLY ST	9,030	75	6.6	96	1475
KB PQ NT	10,860	79	7.0	119	1710
KB PQ ST	10,290	77	6.8	103	1702
KB GLY NT	9,420	74	8.4	102	1556
KB GLY ST	8,850	68	7.6	95	1120
MX PQ NT	10,510	78	7.4	105	1368
MX PQ ST	10,500	85	8.2	110	1579
MX GLY NT	9,090	77	9.3	95	1606
MX GLY ST	9,370	78	8.3	95	1203
	$P > t$				
CF vs. KB	0.814	0.267	0.786	0.859	0.692
CF vs. MX	0.804	0.785	0.997	0.995	0.508
KB vs. MX	0.999	0.568	0.819	0.902	0.941
PQ vs. GLY	<0.001	0.048	0.306	<0.001	0.105
NT vs. ST	0.830	0.461	0.034	0.902	0.572
C vs. CF PQ NT	0.246	0.090	0.075	0.447	0.069
C vs. CF PQ ST	0.307	0.508	0.456	0.122	0.030
C vs. KB PQ NT	0.449	0.885	0.877	0.075	0.126
C vs. KB PQ ST	0.164	0.954	0.988	0.646	0.130
CF PQ NT vs. CF PQ ST	0.866	0.266	0.112	0.333	0.678
KB PQ NT vs. KB PQ ST	0.445	0.831	0.838	0.109	0.985

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

treatments exhibiting large differences in N uptake had similar grain yield. For example, the control accumulated 128 kg ha^{-1} of grain N in 2009 compared to 61 kg ha^{-1} in CF PQ NT and these treatments yielded within 3%. High grain N uptake was not a prerequisite for high grain yields under normal growing season rainfall, which is similar to results reported by Singer et al. (2007) in Iowa.

Plant Density

In 2008, tillage and herbicide affected plant density, although the LM × treatment interaction was marginally significant ($p = 0.056$). In 2009, there were no significant main effects or interactions. In 2010, only herbicide was significant. In 2008, PQ (83,730 plants ha^{-1}) had greater plant density than GLY (79,110 plants ha^{-1}), and NT (83,250 plants ha^{-1}) had greater plant density than ST (79,590 plants ha^{-1}) (Table 2). In 2009, plant density was 81,540 plants ha^{-1} averaged over all treatments (Table 3). In 2010, PQ (74,600 plants ha^{-1}) had greater plant density than GLY (69,880 plants ha^{-1}) (Table 4). Higher stand populations did not necessarily relate to higher yield, kernel number, or differences in TKW in any year.

Stover Dry Matter and Nutrient Uptake

In 2008 and 2009, herbicide ($p < 0.001$ and $p < 0.001$) and the LM × treatment interaction ($p < 0.001$ and $p = 0.007$) were significant. Additionally in 2008, LM ($p = 0.001$), LM × herbicide ($p = 0.031$), and tillage × herbicide ($p = 0.007$) significantly affected SDM. In 2010, LM ($p = 0.009$), tillage ($p < 0.001$), herbicide ($p < 0.001$) and the LM × treatment interaction ($p < 0.001$) were all significant for SDM. All LM treatment means were lower compared to the control in 2008, and CF GLY NT, CF GLY ST, KB GLY NT, KB GLY ST, MX GLY NT, and MX GLY ST were lower in 2009 (Tables 5 and 6). Kentucky bluegrass PQ ST produced the most SDM (6880 kg ha^{-1}) in 2008 after the control, but was not different than KB PQ NT. Paraquat (10,550 kg ha^{-1}) produced more SDM than GLY (9180 kg ha^{-1}) in 2009, averaged across LM and tillage. Although the LM × treatment interaction was significant in 2009, no differences were detected among the no LM control and any LM PQ treatment. In 2010, SDM responses were similar to 2008, although more separation occurred between LM × herbicide × tillage treatments (Table 7). For example, KB PQ ST and CF PQ ST were both significantly higher than the NT treatment within the same LM and herbicide treatment. No difference was detected between CF PQ ST and KB PQ ST ($p = 0.658$). Similar to 2008, all LM treatments had lower SDM than the no LM control in 2010. In 2008 and 2010, KB PQ ST had 22 and 14% lower SDM than the no LM control.

In 2008, LM ($p = 0.003$), herbicide ($p = 0.002$), and the LM × treatment interaction ($p < 0.001$) significantly affected stover nitrogen (SN) uptake. Only herbicide ($p = 0.048$) was significant in 2009 for SN uptake. In 2010, LM ($p = 0.037$), herbicide ($p < 0.001$), tillage × herbicide ($p = 0.020$), and LM × treatment ($p < 0.001$) were significant. In 2008, all treatments had lower SN

Table 7. Treatment means and probability values for living mulch species, tillage, and herbicide for stover (S) dry matter (DM), N, P, and K uptake, and basal stalk nitrate concentration (BSN) in 2010 near Ames, IA.

Treatment	SDM	SN	SP	SK	BSN
		---kg ha^{-1}---			mg NO_3–N kg^{-1}
Control (C)	10,020	63	16	104	343
CF PQ NT†	6,220	45	13	74	747
CF PQ ST	8,360	49	11	87	736
CF GLY NT	3,520	32	9	36	970
CF GLY ST	4,460	37	10	47	1099
KB PQ NT	7,380	55	13	82	1113
KB PQ ST	8,630	49	13	94	464
KB GLY NT	4,860	36	11	53	644
KB GLY ST	5,560	43	12	66	781
MX PQ NT	6,240	46	13	69	715
MX PQ ST	5,850	37	12	73	737
MX GLY NT	3,270	28	9	34	753
MX GLY ST	4,270	36	10	44	963
			P > *t*		
CF vs. KB	0.082	0.205	0.564	0.101	0.722
CF vs. MX	0.188	0.360	0.987	0.530	0.848
KB vs. MX	0.008	0.032	0.649	0.025	0.969
PQ vs. GLY	<0.001	<0.001	0.002	<0.001	0.306
NT vs. ST	<0.001	0.458	0.827	0.004	0.812
C vs. CF PQ NT	<0.001	0.002	0.123	0.001	0.165
C vs. CF PQ ST	0.009	0.012	0.021	0.052	0.176
C vs. KB PQ NT	<0.001	0.142	0.183	0.014	0.010
C vs. KB PQ ST	0.027	0.018	0.169	0.231	0.673
CF PQ NT vs. CF PQ ST	<0.001	0.486	0.261	0.112	0.968
KB PQ NT vs. KB PQ ST	0.038	0.325	0.952	0.157	0.022

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

uptake compared to the no LM control (Table 5). Additionally, although grain yield was different between KB PQ ST and KB PQ NT and SDM trended lower between these treatments (p = 0.064), no difference was detected in SN uptake. Averaged across tillage and herbicide, maize growing in KB accumulated the most SN (42 kg ha^{-1}) and CF the least (33 kg ha^{-1}). Averaged across LM and tillage, maize in PQ (40 kg ha^{-1}) accumulated more SN than maize in GLY (34 kg ha^{-1}). Similar results were observed in 2009, with maize in PQ (82 kg ha^{-1}) accumulating more SN than maize in GLY (75 kg ha^{-1})(Table 6). Unlike 2008, in 2010, no differences were detected between CF and KB, averaged across tillage and herbicide (Table 7). The tillage × herbicide interaction was significant because KB PQ ST and MX PQ ST had lower SN uptake than NT within the same herbicide and LM treatment. In other comparisons, PQ ST had higher SN uptake than the NT comparison. Aside from these differences, all treatments had lower SN uptake compared to the no LM control except KB PQ NT. The higher SN uptake in this treatment likely indicates lower sink demand for N because KB PQ NT yielded 23% less than KB PQ ST with 25% less grain nitrogen uptake (GNU).

Few differences were detected for stover phosphorus (SP) uptake. In 2008, the LM × herbicide interaction affected SP uptake (p = 0.049). In 2009, only tillage was significant (p = 0.034). In 2010, only herbicide was significant for SP uptake (p = 0.002). In 2008, the control had lower SP uptake compared to MX GLY ST and MX PQ NT (Table 5). There were no

Table 8. Treatment means and probability values for living mulch (LM) species, tillage, and herbicide for weed density (WD), LM dry matter (DM), N, P, and K uptake, and percent groundcover (GRND) in 2008 near Ames, IA.

Treatment	WD	LMDM	LMN	LMP	LMK	GRND
	no. m^{-2}		kg ha^{-1}			%
Control	–	–	–	–	–	–
CF PQ NT†	2	3035	63	10.8	54	98
CF PQ ST	3	2667	55	9.0	44	90
CF GLY NT	3	2619	45	8.0	30	98
CF GLY ST	3	2617	42	7.9	30	85
KB PQ NT	4	1262	24	4.0	16	96
KB PQ ST	7	1238	26	3.7	15	84
KB GLY NT	5	1973	34	5.7	20	96
KB GLY ST	1	2268	40	6.5	22	82
MX PQ NT	2	3257	67	11.1	50	98
MX PQ ST	3	3109	65	10.9	48	89
MX GLY NT	1	2905	49	8.5	32	97
MX GLY ST	1	2825	49	9.4	35	89
			P > *t*			
CF vs. KB	0.178	0.005	0.002	0.010	0.006	0.213
CF vs. MX	0.284	0.403	0.238	0.508	0.931	0.923
KB vs. MX	0.022	0.001	<0.001	0.003	0.004	0.131
PQ vs. GLY	0.098	0.531	0.047	0.361	0.002	0.170
NT vs. ST	0.946	0.749	0.785	0.881	0.651	<0.001
CF PQ NT vs. CF PQ ST	0.868	0.380	0.330	0.255	0.157	0.001
KB PQ NT vs. KB PQ ST	0.054	0.954	0.868	0.840	0.897	<0.001

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

significant comparisons to the control in 2009 (Table 6). In 2010, differences were detected among SP uptake and the control including CF PQ ST, which had similar yield as the control (Table 7). In 2008, LM (p = 0.003), herbicide (p < 0.001), LM × tillage (p = 0.041), and tillage × herbicide (p = 0.014) had a significant effect on SK uptake. All treatments were significant in 2008 compared to the no LM control (74 kg ha^{-1})(Table 5), except KB PQ ST (78 kg ha^{-1}), KB PQ NT (66 kg ha^{-1}), and MX PQ NT (63 kg ha^{-1}). In 2009, only herbicide (p < 0.001) was significant for SK uptake. Averaged across LM and tillage, maize in PQ accumulated greater SK (110 kg ha^{-1}) than maize in GLY (94 kg ha^{-1}) (Table 6). In 2010, LM (p = 0.027), tillage (p = 0.004), herbicide (p < 0.001), and the LM × treatment interaction (p < 0.001) were significant. Treatments with similar yield as the no LM control had similar SK uptake, although CF PQ ST compared to the control was at the probability cutoff (p = 0.052).

Basal Stalk Nitrate

Assessing nitrate concentrations using the BSN provides a diagnostic assay that assesses fertilizer N sufficiency. There were no significant main effects or interactions for BSN any year. Basal stalk nitrate averaged 599, 1522, and 774 mg NO_3–N kg^{-1} in 2008, 2009, and 2010, respectively (Tables 5–7). Binford et al. (1990) reported BSN concentrations of 250 mg NO_3–N kg^{-1} as the critical concentration using a linear-response and plateau model, and 1800 mg kg^{-1} NO_3–N as the maximum economic optimum concentration. All of the BSN concentrations were within this range except the control in 2008 (248 mg NO_3–N kg^{-1}) and CF PQ NT (1847 mg NO_3–N kg^{-1}) and CF PQ ST (2021 mg NO_3–N kg^{-1}) in 2009. These results indicate

Table 9. Treatment means and probability values for living mulch (LM) species, tillage, and herbicide for weed density (WD), LM dry matter (DM), N, P, and K uptake, and percent groundcover (GRND) in 2009 near Ames, IA.

Treatment	WD	LMDM	LMN	LMP	LMK	GRND
	no. m^{-2}		kg ha^{-1}			%
Control (C)	–	–	–	–	–	54
CF PQ NT†	8	1139	24	3.5	11	94
CF PQ ST	8	829	17	2.5	7	81
CF GLY NT	5	2447	52	7.5	21	96
CF GLY ST	6	1788	35	5.2	13	88
KB PQ NT	13	592	12	1.8	5	91
KB PQ ST	9	740	14	2.1	6	84
KB GLY NT	5	1250	26	3.9	9	96
KB GLY ST	4	1278	24	3.8	9	88
MX PQ NT	7	984	21	2.9	10	94
MX PQ ST	7	1141	24	3.2	13	87
MX GLY NT	3	1657	35	5.2	17	96
MX GLY ST	4	1586	32	4.6	14	85
			$P > t$			
CF vs. KB	0.697	0.013	0.013	0.014	0.018	0.986
CF vs. MX	0.329	0.361	0.424	0.298	0.958	0.831
KB vs. MX	0.116	0.080	0.064	0.104	0.013	0.746
PQ vs. GLY	0.003	<0.001	<0.001	<0.001	<0.001	0.033
NT vs. ST	0.722	0.206	0.052	0.043	0.041	<0.001
CF PQ NT vs. CF PQ ST	0.874	0.173	0.137	0.106	0.085	0.001
KB PQ NT vs. KB PQ ST	0.184	0.509	0.560	0.583	0.654	0.055

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

Table 10. Treatment means and probability values for living mulch (LM) species, tillage, and herbicide for weed density (WD), LM dry matter (DM), N, P, and K uptake, and percent groundcover (GRND) in 2010 near Ames, IA.

Treatment	WD	LMDM	LMN	LMP	LMK	GRND
	no. m^{-2}		kg ha^{-1}			%
Control (C)	–	–	–	–	–	35
CF PQ NT†	2	1027	21	3.2	14	85
CF PQ ST	4	575	11	1.8	5	62
CF GLY NT	2	3362	65	8.6	40	97
CF GLY ST	4	2570	49	6.4	31	72
KB PQ NT	6	1139	17	2.6	15	84
KB PQ ST	6	843	14	1.9	11	71
KB GLY NT	3	2658	48	5.4	35	98
KB GLY ST	1	2360	41	4.9	31	80
MX PQ NT	3	1204	23	3.2	18	93
MX PQ ST	2	1198	24	3.3	17	70
MX GLY NT	1	3326	63	9.3	46	98
MX GLY ST	1	3238	66	9.7	46	81
			$P > t$			
CF vs. KB	0.696	0.763	0.178	0.513	0.997	0.052
CF vs. MX	0.515	0.213	0.104	0.455	0.112	0.007
KB vs. MX	0.193	0.085	0.009	0.109	0.122	0.292
PQ vs. GLY	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NT vs. ST	0.502	0.038	0.101	0.222	0.082	<0.001
CF PQ NT vs. CF PQ ST	0.218	0.222	0.210	0.319	0.155	<0.001
KB PQ NT vs. KB PQ ST	0.547	0.419	0.697	0.635	0.543	0.002

† CF, creeping red fescue, KB, Kentucky bluegrass, MX, creeping red fescue + white clover mixture, PQ, paraquat, GLY, roundup, NT, no-till, ST, strip-till.

that maize growing in these LMs was not N deficient. Nutrient sufficiency was optimized in this experiment by applying P and K each fall and using starter (2 of 3 yr) and sidedress N. Inclusion of the white clover in the mixture was not included to quantify legume N contributions to maize but rather to test a LM treatment with a different growth habit and functional group.

Weed Density and Composition

The potential for significant interspecies competition has been reported in LM systems (Elkins et al., 1979; Scott et al., 1987; Eberlein et al., 1992;; Zemenchik et al., 2000; Singer et al., 2009). Hall et al. (1992) determined the critical period for maize development varies between the 3rd and 14th leaf stage. They further concluded weed interference can reduce maize leaf area, increase senescence of lower leaves, reduce the availability of PAR to lower leaves, deplete soil moisture, and compete for nutrients. Although considered beneficial, LMs may impede maize growth and development similar to weeds. Therefore, a balance is attempted in these complex managed systems to provide certain ecological functions while minimizing negative competitive effects on the cash crop. Living mulch ($p = 0.026$) and the tillage × herbicide interaction ($p = 0.043$) were significant in 2008, although weed densities were <7 plants m^{-2} (Table 8). Maize in the KB PQ ST had the highest weed density and also the second highest grain yield after the control. Clearly, these weed densities in 2008 were not competitive enough with maize to affect yield. In 2009, only the herbicide main effect was significant ($p = 0.003$) and weed densities did not exceed 13 weeds m^{-2} (Table 9). In 2010, herbicide ($p = 0.001$) and the LM × herbicide interaction ($p = 0.035$) were significant, although weed densities did not exceed 6 weeds m^{-2} (Table 10). No increased trend in weed densities was observed during these three growing seasons and weeds did not likely provide a significant source of competition in addition to the LMs during this study.

Living Mulch Dry Matter and Nitrogen, Phosphorus, and Potassium Uptake

Above average winter and spring precipitation delayed herbicide application and planting in 2008 allowing LMs an additional 2 to 3 wk of unabated growth. In 2008, LM ($p = 0.001$) and the LM × herbicide interaction ($p = 0.012$) were significant for LMDM. In 2009, LM ($p = 0.015$), herbicide ($p < 0.001$), LM × tillage ($p = 0.027$), and LM × herbicide ($p = 0.026$) were significant. In 2010, tillage ($p = 0.038$) and herbicide ($p < 0.001$) were significant for LMDM. Generally, KB treatments within a herbicide treatment produced the least quantity of LMDM and consequently had the least negative effect on grain yield (Tables 8–10). In KB PQ ST, LMDM ranged between 740 and 1238 kg ha^{-1}. The 1238 kg ha^{-1} occurred in 2008 when field conditions were too wet to access the field with typical equipment. The inability to manage the LMs under such conditions presents one of the greatest risks in LM production systems. In the other 2 yr, LMDM was fairly similar at 740 and 843 kg ha^{-1}.

All 3 yr, LM ($p < 0.001$, $p = 0.014$, and $p = 0.011$ in 2008, 2009, and 2010) and herbicide ($p = 0.047$, $p < 0.001$, and $p < 0.001$ in 2008, 2009, and 2010) affected living mulch nitrogen uptake (LMN). In 2008 and 2009, the LM × herbicide interaction ($p = 0.001$ and $p = 0.036$) was significant. The LM × tillage interaction was significant ($p = 0.022$) only in 2009. Living mulch N uptake followed LMDM closely (Tables 8–10). In 2008, MX PQ (66 kg ha^{-1}) accumulated the most

N and KB PQ (25 kg ha^{-1}) the least, averaged across tillage. In 2009, CF GLY NT (52 kg ha^{-1}) accumulated the most N. All 3 yr, KB PQ NT and KB PQ ST accumulated the least N among LM treatments (25, 13, and 16 kg N ha^{-1}on average in 2008, 2009, and 2010), except for CF PQ ST in 2010 (11 kg N ha^{-1}).

Living mulch phosphorus uptake (LMP) followed a similar pattern as DM and N uptake. In 2008, LMP was affected by LM ($p = 0.003$) and the LM × herbicide interaction ($p = 0.011$). In 2009, LM ($p = 0.017$), tillage ($p = 0.043$), herbicide ($p < 0.001$), LM × tillage ($p = 0.021$), and LM × herbicide ($p = 0.041$) were significant. In 2010, only herbicide ($p < 0.001$) was significant for LMP. Creeping red fescue PQ (9.9 kg ha^{-1}) accumulated the most P compared to all LM × herbicide treatments in 2008, averaged across tillage (Table 8). In 2009, CF GLY NT (7.5 kg ha^{-1}) accumulated the greatest P (Table 9). Kentucky bluegrass PQ ST and KB PQ NT accumulated the least P all 3 yr, while CF PQ ST also had similar low uptake values in 2009 and 2010 (Table 10). In 2010, P uptake in PQ was 7.4 kg ha^{-1} compared to 2.6 kg ha^{-1} in GLY, averaged across LM and tillage.

Living mulch potassium uptake (LMK) was affected by LM ($p = 0.003$), herbicide ($p = 0.002$), and the LM × herbicide interaction ($p = 0.003$) in 2008. In 2009, LM ($p = 0.009$), tillage ($p = 0.041$), and herbicide ($p < 0.001$) main effects, and the LM × tillage ($p = 0.005$) and tillage × herbicide interactions ($p = 0.042$) were significant for LMK. In 2010, only herbicide ($p < 0.001$) was significant for LMK. In 2008, CF PQ and MX PQ (49 and 49 kg ha^{-1}) accumulated the greatest K averaged across tillage, while KB PQ (16 kg ha^{-1}) accumulated the least (Table 8). In 2009, CF GLY NT (21 kg ha^{-1}) accumulated the greatest K, and KB PQ NT (5.0 kg ha^{-1}) accumulated the least (Table 9). In 2010, CF PQ ST accumulated the least LMK (5 kg ha^{-1}), while KB PQ NT and KB PQ ST had similar LMK (13 kg ha^{-1}).

Percent Total Groundcover

In 2008, only tillage ($p < 0.001$) was significant, although no groundcover data were collected in the control. Averaged across LM and herbicide, NT averaged 97% groundcover compared to 87% in ST (Table 8). In 2009, tillage ($p < 0.001$), herbicide ($p = 0.033$), and the LM × treatment interaction ($p < 0.001$) were significant. The control had the lowest groundcover (54%)(Table 9) and was significantly lower than all treatments. Averaged across LM and herbicide, NT provided 95% groundcover compared to 86% in ST. Averaged across LM and tillage, PQ provided 89% groundcover compared to 92% in GLY. In 2010, LM ($p = 0.008$), tillage ($p < 0.001$), herbicide ($p < 0.001$), and LM × treatment ($p < 0.001$) were significant. In 2010, the control had the lowest groundcover (35%)(Table 10) and was significantly lower than all treatments. Among LM treatments, groundcover ranged between 62 and 98%. Similar to previous years, NT had greater groundcover than ST and GLY had greater groundcover than PQ. Among LMs, MX (86%) had greater groundcover than CF (79%), averaged across tillage and herbicide. Scott et al. (1987) found similar groundcover results using cover crops and living mulches in maize polyculture systems.

CONCLUSIONS

Innovative biomass production systems using LMs to mitigate effects of harvesting greater quantities of maize stover can also maintain competitive maize grain yields. Kentucky bluegrass exhibited the least competitive effects when combined with PQ and fall ST. Achieving high yields occurred through maintenance of kernel number and was not necessarily related to nutrient uptake. This treatment, however, was only one of 12 LM treatments evaluated in this experiment, which demonstrates the potential for significant competition if insufficient suppression of the LM does not occur. Living mulches extend the beneficial ecological functions of annual cover crops including soil cover, nutrient capture, and organic matter inputs and may facilitate the development of sustainable and profitable maize biomass feedstock production systems. Additional research under varying climate conditions will quantify the risk of using LMs in maize production.

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