Published February 28, 2013

Corn Performance under Managed Drought Stress and in a Kura Clover Living Mulch Intercropping System

Cathrine Ziyomo, Kenneth A. Albrecht, John M. Baker, and Rex Bernardo*

ABSTRACT

A corn (*Zea mays* L.) and kura clover (*Trifolium ambiguum* M. Bieb.) intercropping system provides ecological services, but competition for water between the grain crop and the living mulch crop often reduces corn yields. Our objectives were to determine (i) if corn that performs well under managed drought (i.e., drought-tolerant corn) can minimize the grain yield losses incurred when corn is intercropped with kura clover, and (ii) if strong suppression of the kura clover living mulch minimizes the loss in yield of drought-tolerant and drought-susceptible corn. From drought trials in Minnesota in 2009 and 2010, we identified five drought-tolerant and five drought-susceptible hybrids from the intermated B73 × Mo17 population. Under drought conditions, mean grain yields were 9.66 Mg ha^{-1} for the drought-tolerant hybrids and 5.46 Mg ha^{-1} for the drought-susceptible hybrids. The 10 hybrids were evaluated in Minnesota and Wisconsin in 2011 in a kura clover intercropping system. Drought-tolerant hybrids had statistically equal mean yields of 12.90 Mg ha^{-1} in the killed mulch treatment and 13.69 Mg ha^{-1} in the living mulch treatment. In contrast, mean yields of drought-susceptible hybrids were significantly reduced from 4.53 Mg ha^{-1} in the killed mulch treatment to 3.48 Mg ha^{-1} in the living mulch treatment. For the drought-tolerant hybrids, mulch recovery at corn harvest was significantly lower with killed kura clover (41%) than with living kura clover (50%). Our results indicate that the yield of drought-tolerant corn was not reduced by growing in a living mulch of kura clover.

Corn in the United States is predominantly grown in monoculture. An alternative is to grow corn with a living-mulch cover crop that provides groundcover throughout the growing season. A living mulch provides permanent groundcover, reduces soil erosion (Wall et al., 1991), suppresses weed growth (Enache and Ilnicki, 1990), and reduces pest incidence (Litsinger and Moody, 1976). In addition to these ecological and environmental benefits, the use of a leguminous living mulch can improve the soil nutrient status by releasing symbiotically fixed N_2 to the soil (Scott et al., 1987; Brown et al.,1993) and by reducing NO_3 leaching (Ochsner et al., 2010).

Kura clover is an extremely persistent, perennial legume that spreads by rhizomes (Kim, 1996) and is an excellent candidate as a living mulch in the U.S. Corn Belt (Zemenchik et al., 2000). Researchers at the University of Wisconsin-Madison have developed a living mulch system where the kura clover is established for at least 1 yr, bands of the kura clover are suppressed or killed, and corn is planted in the killed or suppressed bands (Albrecht et al., 2000). To facilitate the germination and development of corn, suppression of the living mulch is managed to sufficiently reduce competition with the corn crop yet still allow regrowth and recovery of the living mulch. Dependable corn yields have been obtained with herbicide suppression of kura clover, particularly with herbicide-resistant corn hybrids (Albrecht et al., 2000; Zemenchik et al., 2000; Ochsner et al., 2010). Furthermore, most or all of the corn N requirements are met without fertilizer application in this living-mulch system (Berkevich, 2008).

Despite the ecological benefits of intercropping corn with a living mulch, yield losses due to competition between the living mulch and the grain crop have prevented the widespread use of such a cropping system (Duiker and Hartwig, 2004). Grain yield reductions have been mostly attributed to poor corn emergence and moisture stress as the living mulch competes with the grain crop for water (Box et al., 1980; De Haan et al., 1997). In Wisconsin, reductions in corn grain yield when corn is grown with kura clover have ranged from 8 to 30% (Zemenchik et al., 2000; Affeldt et al., 2004; Ochsner et al., 2010). Under dry conditions, increased suppression of the kura clover does not always lead to high corn yields, and the living mulch may also fail to recover if the suppression is excessive (Bard, 2009). A successful corn–kura clover cropping system would therefore involve reducing the water demands of both the cover crop and the grain crop at critical developmental stages of the grain crop. Furthermore, previous research has also indicated that companion crops can delay corn growth and physiological development through reduced soil temperatures at the time of planting (Heyland and Werner, 1988).

The use of drought-tolerant corn is one way to combine the environmental and economic benefits of a kura clover living mulch with high corn yields and to minimize the risk associated

C. Ziyomo, and R. Bernardo, Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, 411 Borlaug Hall, 1991 Upper Buford Circle, Saint Paul, MN 55108; K.A. Albrecht, Dep. of Agronomy, Univ. of Wisconsin, 1575 Linden Drive, Madison, WI 53706; and J.M. Baker, Soil and Water Management Research Unit, USDA-ARS, 439 Borlaug Hall, 1991 Upper Buford Circle, Saint Paul, MN 55108. Received 5 Nov. 2012. *Corresponding author (bernardo@umn.edu).

Published in Agron. J. 105:579–586 (2013)
doi:10.2134/agronj2012.0427

Abbreviations: ASI, anthesis–silking interval.

with this cropping system. This could potentially accelerate the adoption of living mulches in corn production and may allow increased stover removal for cellulosic ethanol production. If the drought-tolerant corn is competitive enough with the living mulch early in the season, the amount of herbicide required to suppress the living mulch could be reduced and nonherbicide mulch suppression strategies might become feasible, e.g., tillage, mechanical mowing, or thermal suppression (Grubinger and Minotti, 1990; Costello and Altieri, 1994; Bard, 2009). No published information is currently available on the impact of drought-tolerant corn in a kura clover living mulch system.

Our objectives in this study were to determine (i) if corn that performs well under managed drought (i.e., drought-tolerant corn) can minimize the grain yield losses incurred when corn is intercropped with kura clover, and (ii) if strong suppression of the kura clover living mulch minimizes the loss in grain yield of drought-tolerant and drought-susceptible corn. Drought tolerance has been defined as the "ability of a plant to live, grow, and reproduce satisfactorily with limited water supply or under periodic conditions of water deficit" (Turner, 1979; Fleury et al., 2010). This definition of drought tolerance does not consider how a drought-tolerant cultivar performs under nondrought conditions. As explained below, we used a drought index to select for drought tolerance primarily based on grain yield under drought and with only minimal regard for grain yield under nondrought conditions (Bolaños and Edmeades, 1993); however, the correlation between corn grain yield under stress and nonstress conditions is often moderate to high (Bänziger et al., 1997, 1999; Campos et al., 2004; Zaidi et al., 2008; Ziyomo, 2012). As such, the drought-tolerant hybrids in this study also tended to be the most productive hybrids under nonstress conditions and, conversely, the drought-susceptible hybrids also tended to be the least productive under nonstress conditions.

MATERIALS AND METHODS

Plant Materials and Drought Stress Evaluation

The intermated B73 × Mo17 population is a set of recombinant inbreds developed after six generations of selfing plants from a random-mated F_2 population (Lee et al., 2002). Both B73 and Mo17 have been used extensively in the development of commercial hybrids in the U.S. Corn Belt. A total of 238 intermated B73 × Mo17 recombinant inbreds, along with the inbred parents B73 and Mo17, were testcrossed to a proprietary Monsanto inbred tester (LH295) that performed well when crossed with both B73 and Mo17.

The testcross hybrids were evaluated for drought tolerance at the Anoka Sand Plain Research Station (45°35′ N, 93°10′ W), Minnesota, in 2009 and 2010. The soils at Anoka are light-textured loamy sand with poor natural drainage, hence a low water holding capacity. Drought stress was managed by withholding irrigation so that moisture stress was severe enough to delay silking and cause ear abortion and ultimately reduce yield by approximately 50% (Bänziger et al., 2000). Control experiments, which received supplementary irrigation, were planted alongside the drought experiments. The drought and control experiments were conducted in an augmented randomized complete block design experiment (Federer, 1961) with five check hybrids replicated eight times. The hybrids were grown in two-row plots, each row 6.6 m long and spaced 0.76 m apart, and at a plant population density of 72,000 plants ha^{-1} in the control experiments. In the drought experiments, the plots were 4.5 m long and had a plant population density of 66,000 plants ha^{-1}. At planting, both the control and the drought-stress experiments received the recommended amounts of irrigation; however, irrigation was stopped after 6 wk in the drought-stress experiment. In 2009, the control experiment received a total of 753 mm of water as both rainfall (59 mm of rainfall in July and 143 mm in August) and irrigation, whereas the drought-stress experiment received 360 mm of water. In 2010, the control experiment received 989 mm as both rainfall (71 mm of rainfall in July and 150 mm in August) and irrigation, whereas the drought-stress experiment received 750 mm of water.

Drought stress has been known to delay silk emergence (Bolaños and Edmeades, 1993), and the anthesis–silking interval (ASI) was recorded as the difference, measured in days, between silking and pollen shed. Leaf senescence or stay-green was recorded 2 wk after flowering as a visual score on a scale of zero (low senescence) to 10 (high senescence). Leaf chlorophyll content was measured with a Minolta 502 chlorophyll SPAD meter. Readings in SPAD units were taken on the third leaf from the tassel and on the ear leaf during flowering. The measurements were taken on five alternating plants from each plot, midway between the stalk and leaf tip and between the midrib and the edge of the leaf. Plant and ear heights were measured at physiological maturity as the visually determined average for each plot. Plant height was measured as the distance from the soil surface to the tip of the tassel, while ear height was measured as the distance from the soil surface to the node of the ear leaf. At physiological maturity, root lodging was measured as the percentage of plants that were inclined at an angle >45° and stalk lodging was measured as the percentage of plants with stalks broken below the ear. Grain yield was determined by hand harvesting the ears from 3 m of each row at maturity. Grain moisture was obtained by oven drying a 500-g sample from each plot. Final grain yields were estimated from shelled grain weight per plot after adjusting to 155 g H_2O kg^{-1} moisture content.

Selection of Drought-Tolerant and Drought-Susceptible Hybrids

A selection index was used to combine information from different traits related to drought tolerance. First, the means for each trait of each of the 240 hybrids were calculated across the 2009 and 2010 drought-stress experiments and were likewise calculated across the 2009 and 2010 control experiments. For each hybrid, the means from the drought-stress experiments were used to construct a yield index as I = (grain yield in Mg ha^{-1}) – 0.028(grain moisture in g H_2O kg^{-1}) – 0.059(stalk lodging percentage) – 0.036(root lodging percentage), where the weights are the respective weights that have been used by commercial corn breeders (Bernardo, 1991). A yield index for each hybrid was likewise calculated from the means from the control experiments.

Second, a drought index was constructed by combining information from the (i) yield index in the drought experiments; (ii) yield index in the control experiments; (iii) ASI from the drought experiments; and (iv) leaf senescence from the drought experiments. Based on empirical data from CIMMYT (Edmeades et al., 1997), we assigned the following weights to each component of the drought index: 4 for the yield index in the drought experiments; 2 for ASI; 1 for the yield index in the control experiments; and 1 for leaf senescence. The yield index in the control experiments was included in the drought index to help guard against the selection of hybrids that would have poor performance under nondrought conditions (Bolaños and Edmeades, 1993). The drought index was calculated as the sum of the ranks (Kang, 1988) multiplied by their respective weights. For example, hybrid MO093 had the highest yield (rank of 240) in the drought experiments, had moderately high yield (rank of 227) in the control experiments, and had the best ASI and leaf senescence (ranks of 240). The drought index of hybrid MO093 was then (4)240 + (1)227 + 2(240) + 1(240) = 1907. The five hybrids with the highest drought indices were identified as the drought-tolerant hybrids for evaluation in the kura clover living mulch experiments. Likewise, the five hybrids with the lowest drought index were identified as the drought-susceptible hybrids for further evaluation.

Kura Clover Experiments

The 10 hybrids chosen for their drought tolerance and drought susceptibility were evaluated in 2011 at three locations: the University of Wisconsin Arlington Agricultural Research Station (43°18′ N, 89°21′ W); the University of Wisconsin Lancaster Agricultural Research Station (42°49′ N, 90°47′ W); and the University of Minnesota Rosemount Research and Outreach Center (44°71′ N, 93°7′ W). At each location, the kura clover had been established at least 2 yr beforehand and was approximately 15 cm tall at the time of corn planting. Corn was planted in four-row plots, each 6.6 m long and spaced 0.76 m apart, at a plant population density of 80,000 plants ha^{-1}. At each location, the 20 treatments comprised a factorial combination of the 10 hybrids and two levels of kura clover suppression (killed or living). The experiments were conducted in a randomized complete block design with four replications. No supplementary irrigation was supplied. At each location, a recommended total of 50 kg ha^{-1} N fertilizer in the form of NH_4NO_3 was applied 30 d after planting to ensure that N was not limiting corn growth. The remaining corn N requirements were assumed to be met by N release from killed or suppressed kura clover (Affeldt et al., 2004; Berkevich, 2008).

Three weeks before corn planting, suppressed or killed kura clover plots were created by application of glyphosate [*N*-(phosphonomethyl)glycine] at a rate of 1.26 kg a.i. ha^{-1} or glyphosate plus 0.42 kg a.i. ha^{-1} of clopyralid (3,6-dichloro-2-pyridinecarboxylic acid), respectively (Affeldt et al., 2004). Previous research has demonstrated that spring application of glyphosate suppresses but does not kill kura clover (Zemenchik et al., 2000). One week after planting, but before corn emergence, a second application of glyphosate was made to all plots to kill any emerging weeds and further suppress kura clover. At this time, a 25-cm band of clopyralid (0.42 kg a.i. ha^{-1}) was applied over the corn rows in the suppressed treatment. A four-row no-till corn planter was used to open furrows and corn was hand planted and furrows manually closed at Arlington and Lancaster. At Rosemont, a four-row White Model 6104 no-till planter was used for planting.

Plant and ear height, ASI, root and stalk lodging, leaf senescence, stand counts, and grain yield and moisture content in the kura clover plots were measured from the middle two rows of each plot in the same manner as in the drought-stress experiments. In addition, kura clover regrowth was measured based on a visual assessment of the percentage of groundcover on the plot area, with zero indicating no groundcover and 100 indicated total groundcover.

Data Analysis

For both the drought experiments and kura clover experiments, SAS Version 9.2 PROC MIXED (SAS Institute, 2008) was used for ANOVA. In the drought experiments, the effects of years and hybrids and of interactions that involved years or hybrids were considered random, whereas the effects of levels of drought stress were considered fixed. In the kura clover experiments, the effects of locations and of interactions that involved locations were considered random, while the effects of the 10 hybrids and the two levels of kura clover suppression were considered fixed. Least significant differences ($P = 0.05$) were calculated from ANOVA within each experiment, and single degree of freedom contrasts were used to compare the effects of groups of corn hybrids (drought tolerant and drought susceptible).

RESULTS AND DISCUSSION

Corn Grain Yield and Agronomic Traits in Drought Experiments

In the experiments at Becker, MN, in 2009 and 2010, all main effects (hybrids, drought stress, and years) and all interaction effects were significant ($P \leq 0.05$) for all traits studied except for leaf chlorophyll content, for which the mean squares for hybrids, hybrid × drought stress interaction, and hybrid × drought stress × year interaction were not significant. The significant hybrid × drought stress interaction for all traits except leaf chlorophyll content indicated differential responses of the 240 hybrids to drought stress.

Mean grain yields of the 240 hybrids were 12.36 Mg ha^{-1} in the control experiments and 6.49 Mg ha^{-1} in the drought stress experiments. Drought stress therefore reduced grain yields by about 47%, which was close to the target reduction of 50% (Bänziger et al., 2000). Mean grain yields for the five drought-tolerant hybrids (identified as those with the highest drought index values) were 13.87 Mg ha^{-1} in the control experiments and 9.66 Mg ha^{-1} in the drought-stress experiments, and the difference between these two means was significant (Table 1). The five drought-tolerant hybrids were among the 20 highest yielding hybrids in both the drought-stress experiments and the control experiments. Similar results have been reported in both tropical and temperate corn, where improvements to abiotic stresses have been associated with high yields under nonstress growing conditions (Edmeades et al., 1993; Duvick, 2005).

The mean yield of the drought-susceptible hybrids was significantly higher in the control experiments (7.11 Mg ha^{-1}) than in the drought experiments (5.46 Mg ha^{-1}; Table 1). Relative to the control experiments, drought stress therefore reduced grain yields by 30% (4.21 Mg ha^{-1}) among the drought-tolerant hybrids and by 23% (1.65 Mg ha^{-1}) among the drought-susceptible hybrids. A linear contrast (mean reduction in Table 2) revealed a significant difference ($P \leq 0.05$) between these 4.21 Mg ha^{-1} vs. 1.65 Mg ha^{-1} yield reductions (Table 2).

The larger absolute reduction and percentage reduction due to drought among the drought-tolerant hybrids (4.21 Mg ha^{-1} and

Table 1. Trait means for the drought-tolerant and drought-susceptible corn hybrids in control (nondrought) and drought experiments at Becker, MN, in 2009 and 2010.

Hybrid	Control							Drought						
	Yield	Moisture	ASI†	Plant height	Ear height	Senescence	Chlorophyll	Yield	Moisture	ASI	Plant height	Ear height	Senescence	Chlorophyll
	Mg ha^{-1}	g kg^{-1}	d	—— cm ——		%	SPAD units	Mg ha^{-1}	g kg^{-1}	d	—— cm ——		%	SPAD units
Drought-tolerant hybrids														
MO011	14.55	279	1	280	125	0	63.2	9.42	273	1	265	100	10	48.8
MO080	12.67	281	−1	275	120	10	57.2	8.64	271	−1	270	110	15	45.2
MO093	14.27	340	1	290	120	5	54.4	10.73	255	1	329	115	10	50.1
MO114	14.61	299	1	290	130	10	62.5	9.88	243	1	301	100	15	42.4
MO179	13.26	300	1	285	125	5	60.8	9.67	261	1	301	120	0	41.7
Mean	13.87	299	1	284	124	6	59.6	9.66	260	1	293	110	10	45.6
Drought-susceptible hybrids														
MO008	7.25	264	0	265	110	10	51.5	3.25	253	6	245	90	45	33.3
MO054	8.37	278	0	275	115	5	53.2	4.62	268	5	240	95	35	43.7
MO062	5.78	257	1	270	105	5	49.0	7.29	236	8	250	100	45	37.3
MO104	9.38	269	1	280	125	10	54.9	4.38	216	6	255	95	50	45.8
MO198	4.76	256	1	270	120	0	56.7	7.76	221	8	240	80	50	38.2
Mean	7.11	265	1	272	115	6	53.1	5.46	239	7	246	92	44	39.7
$LSD_{0.05}$	2.18	6	NS‡	9	6	NS	NS	1.74	NS	2	11	6	7	4.9

† ASI, anthesis–silking interval.
‡ NS, not significant at $P = 0.05$.

30%) than among the drought-susceptible hybrids (1.65 Mg ha^{-1} and 23%) may seem to indicate that the five drought-tolerant hybrids should not be considered as drought tolerant after all. From a practical perspective, however, the higher mean yields in the drought experiments of the five drought-tolerant hybrids (9.66 Mg ha^{-1}) compared with the five drought-susceptible hybrids (5.46 Mg ha^{-1}) indicated that a producer would still be much better off growing the drought-tolerant hybrids if drought is present. The definition of drought tolerance given by Turner (1979), which does not consider the performance of a cultivar under nondrought conditions, therefore maximizes yield performance under drought. The ideal situation is for a drought-tolerant hybrid to have zero or minimal yield losses under drought stress. As previously indicated, correlations between corn grain yield under stress and nonstress conditions are often moderate to high (Bänziger et al., 1997, 1999; Campos et al., 2004; Zaidi et al., 2008), and the genetic correlation between hybrid performance in the drought vs. control experiments in this study was 0.61 (Ziyomo, 2012). Zero or minimal yield losses due to drought in a drought-tolerant corn hybrid are therefore unlikely unless such drought tolerance is due to transgenes that confer drought tolerance but have minimal effects on yield under nondrought conditions (Gilbert, 2010).

In the control experiments, no significant differences were detected for ASI, leaf senescence, or leaf chlorophyll content (Table 1). Similar results for these traits have been consistently observed in previous studies where corn was grown in different environments with varying levels of stress (Ribaut et al., 1996; Betrán et al., 2003). The lack of significant differences for these traits in the control experiment implied that such traits are adaptive and are more important under drought than in nondrought environments (Bänziger et al., 2000).

In the drought experiments, the mean ASI was 1 d among the drought-tolerant hybrids and 7 d among the drought-susceptible hybrids (Table 1). Mean leaf senescence under drought stress was significantly lower (Table 2) among the drought-tolerant hybrids (10%) than among the drought-susceptible hybrids (44%), and conversely, chlorophyll content was higher in the drought-tolerant hybrids (45.6) than the drought-susceptible hybrids (39.7). Grain moisture content was lower in the drought experiments than in the control experiments for both the drought-tolerant and drought-susceptible hybrids. The lower grain moisture for the drought-susceptible hybrids suggested a shorter grain filling period in the drought-susceptible hybrids, which in turn contributed significantly to the lower grain yields.

Corn Grain Yields and Agronomic Traits in Living Mulch Experiments

The Arlington, Lancaster, and Rosemount locations differed in their mean temperatures and total precipitation during the 2011 growing season (Table 3). Total precipitation between May and September was 341 mm at Arlington, 452 mm at Rosemount, and 521 mm at Lancaster (Table 3). The total precipitation at Arlington was substantially lower than the 30-yr historical average of 509 mm, indicating drought-like conditions during the growing season.

Means squares for hybrid × suppression-level interaction were significant ($P \leq 0.05$) for each trait studied, indicating

Table 2. Linear contrasts for corn agronomic traits in the drought experiments at Becker, MN, in 2009 and 2010 and the living mulch experiments at Arlington and Lancaster, WI, and Rosemount, MN, in 2011.

Contrast	Significance							
	Yield	Moisture	ASI†	Senescence	Plant height	Ear height	Regrowth	Plant population density
Drought experiments								
Control vs. drought (drought-tolerant hybrids)	*	NS	NS	NS	*	NS		
Control vs. drought (drought-susceptible hybrids)	*	*	*	*	NS	NS		
Mean reduction of drought-tolerant vs. drought-susceptible hybrids	*	*	*	*	*	NS		
Kura clover experiments								
Living mulch vs. killed (drought-tolerant hybrids)	NS	NS	NS	NS	NS	NS	*	NS
Living mulch vs. killed (drought-susceptible hybrids)	*	*	NS	*	NS	*	*	*
Mean reduction of drought-tolerant vs. drought-susceptible hybrids	*	*	*	*	*	*	*	NS

* Significant that the $P < 0.05$ level; NS, not significant.

† Anthesis–silking interval.

Table 3. Mean precipitation and monthly temperatures during the 2011 growing season at Arlington and Lancaster, WI and Rosemount, MN.

Month	Arlington		Lancaster		Rosemount	
	Precipitation	Temperature	Precipitation	Temperature	Precipitation	Temperature
	mm	°C	mm	°C	mm	°C
May	40	12.1	59	14.6	118	18.6
June	104	28.2	137	19.8	112	24.6
July	63	29.7	176	31.9	126	29.6
Aug.	37	22.9	59	21.0	80	26.8
Sept.	98	18.6	91	15.8	16	21.9
Mean	68	22.3	104	20.6	90	24.3
Total	341		521		452	
30-yr mean (May–Sept.)	509		538		537	

that the 10 individual hybrids differed in their responses to the level of kura clover suppression. The drought-tolerant hybrids (as a group) and drought-susceptible hybrids (as a group) differed in their mean response to the kura clover. For the drought-tolerant hybrids, the mean grain yield was 12.90 Mg ha^{-1} in the killed mulch treatment and 13.69 Mg ha^{-1} in the living mulch treatment (Table 4). For the drought-susceptible hybrids, the mean grain yield was 4.53 Mg ha^{-1} in the killed mulch treatment and 3.48 Mg ha^{-1} in the living mulch treatment. Unlike the drought-tolerant hybrids, the mean grain yields of the drought-susceptible hybrids differed significantly ($P \leq 0.05$) between the killed and living mulch treatments (Table 2). This result for the drought-susceptible hybrids was consistent with the results from the monoculture drought-stress experiments at Becker in 2009 and 2010. For the drought-tolerant hybrids, the nonsignificant 6% difference in mean yield between the killed and living mulch treatments was slightly lower than the 8 to 14% reductions in yield for hybrids not selected for drought tolerance or susceptibility (Zemenchik et al., 2000; Affeldt et al., 2004); however, the 22% reduction in mean yield for the drought-susceptible hybrids was larger than the yield reductions previously reported by Zemenchik et al. (2000) and Affeldt et al. (2004). These results suggest that drought tolerance is indeed a key factor for maintaining corn grain yields in a kura clover living mulch system.

In addition to higher yields, the drought-tolerant hybrids had a significantly shorter ASI, taller plants, lower senescence scores, and higher grain moisture contents (for both the living mulch treatment and the killed treatment) compared with the drought-susceptible hybrids (Table 4). Leaf senescence of the drought-susceptible hybrids was lower in the killed treatment than in the living mulch treatment. No significant difference in mean leaf senescence between the killed and living mulch treatments was found for the drought-tolerant hybrids (Table 2). This result may have been due to the drought-tolerant hybrids also being tolerant to low soil N. In particular, the 10 hybrids selected for their drought tolerance and susceptibility in this study have also been evaluated for their performance under low-N conditions (Ziyomo, 2012). The five drought-tolerant hybrids were among the top 10 highest yielding hybrids under low-N conditions, and the genetic correlation between grain yield under drought stress and grain yield under low N among all hybrids was 0.65 ($P \leq 0.05$). Zemenchik et al. (2000) and Berkevich (2008) found that kura clover can meet the N requirements during the first year of corn production, and the enhanced low-N tolerance of drought-tolerant hybrids (Bänziger et al., 1999) could lead to minimal N fertilizer requirements in the kura clover living mulch system.

For the drought-tolerant hybrids, the mean grain moisture was 317 g H_2O kg^{-1} in the killed mulch treatment and 326 g H_2O kg^{-1} in the living mulch treatment (Table 4). For the

Table 4. Trait means for the drought-tolerant and drought-susceptible corn hybrids at two levels of kura clover living mulch suppression at Arlington and Lancaster, WI, and Rosemount, MN, in 2011.

Hybrid	Killed kura clover							Living mulch						
	Yield	Moisture	ASI†	Plant height	Ear height	Senescence	Regrowth	Yield	Moisture	ASI	Plant height	Ear height	Senescence	Regrowth
	Mg ha^{-1}	g kg^{-1}	d	cm		%		Mg ha^{-1}	g kg^{-1}	d	cm		%	
Drought-tolerant hybrids														
MO011	12.37	284	3	285	130	10	40	13.26	297	0	290	135	5	50
MO080	13.25	321	1	270	120	20	50	12.75	310	1	275	125	10	55
MO093	14.84	395	2	290	130	5	40	13.78	357	1	285	130	5	50
MO114	13.41	306	2	280	120	10	30	14.86	345	2	290	130	0	40
MO179	14.63	277	3	275	125	15	45	13.82	322	0	280	120	10	55
Mean	12.90	317	2	280	125	12	41	13.69	326	1	284	127	6	50
Drought-susceptible hybrids														
MO008	4.12	216	4	265	95	25	50	2.88	227	6	235	80	35	65
MO054	5.25	255	5	250	90	20	75	4.76	267	4	240	85	40	75
MO062	5.46	241	4	260	100	15	60	4.10	274	5	240	90	30	70
MO104	4.47	194	4	255	100	25	65	3.53	231	4	245	85	25	75
MO198	3.37	147	3	260	85	10	55	2.14	183	7	230	80	40	80
Mean	4.53	210	4	258	94	19	61	3.48	236	5	238	84	34	73
$LSD_{0.05}$	1.21	6	NS‡	10	6	NS	15	2.47	21	NS	8	5	NS	6

† ASI, anthesis–silking interval.
‡ NS, not significant at $P = 0.05$.

drought-susceptible hybrids, the mean grain moisture was 210 g H_2O kg^{-1} in the killed mulch treatment and 236 g H_2O kg^{-1} in the living mulch treatment. The contrast of grain moisture content between the tolerant and susceptible hybrids was significant ($P \leq 0.05$). As in the drought experiments at Becker, the lower moisture content for the drought-susceptible hybrids in both the killed and living mulch treatments could have been due to a shorter grain filling period because the plants shorten their life cycle to avoid prolonged exposure to drought stress.

Kura Clover Growth and Recovery after Herbicide Suppression

Kura clover is a weaker competitor for limiting resources than other deeper rooted perennial legumes such as alfalfa (*Medicago sativa* L.) (Albrecht et al., 2000). As a cover crop, this characteristic is favorable because the kura clover will impose a less severe moisture stress on the grain crop. From an ecological perspective, however, this characteristic is unfavorable because it may allow weeds to thrive. Differences in growth habit and phenology between corn and kura clover make them highly compatible, and this compatibility also allows flexibility in the timing of kura clover management or suppression to reduce competition during critical periods.

Dependable corn yields in living mulch systems are directly related to the amount of groundcover retained after suppression, with less groundcover resulting in higher yields. Little clover was maintained in any of the plots until corn flowering as light availability became limited under the dense corn canopy. The kura clover began to spread between the corn rows during grain filling, however, as corn leaves senesced and light reached the clover canopy. As expected, mulch recovery was higher and more rapid in the living mulch plots than in the killed plots, where suppression was severe for both drought-tolerant and drought-susceptible plots (Table 4). Similar results have been previously reported (Affeldt et al., 2004). Overall, mulch recovery was higher with the drought-susceptible hybrids than with the drought-tolerant hybrids (Table 4). Reduced groundcover in the drought-tolerant hybrids could be attributed to poor solar radiation for the kura clover due to shading by the corn once it was fully established. In a study of sod maintenance in row crop systems, favorable yields were maintained with up to 60% living mulch groundcover (Elkins et al., 1983). The 50% groundcover observed for the drought-tolerant hybrids is evidence that a living mulch system can be successfully managed to combine high yields with the ecological benefits of a living mulch system. For the drought-tolerant corn, the lack of a significant yield response to mulch suppression treatments suggests that drought-tolerant corn can be sown in an established kura clover stand with suppression of only the kura clover bands where the corn will be planted. This strategy could significantly reduce dependence on herbicide application for temporarily inhibiting living mulch growth and suppressing weeds.

In addition to reduced kura clover groundcover, weed growth and establishment was minimal in the drought-tolerant plots. Weed pressure was most critical at the onset of the tasseling stage at the Rosemount location, necessitating the need for a second application of herbicides to reduce the penalty on corn yield. Although variable results have been obtained from studies that focused on the critical time for weed management in a living mulch system, there is a consensus that weed pressure is more detrimental to corn grain yield if it is early in the season rather than at later developmental stages (Bosnic and Swanton, 1997; Abdin et al., 2000).

CONCLUSIONS

Drought-tolerant corn can improve the economic productivity and sustainability of living mulch cropping systems by maintaining high corn yields and allowing regrowth and survival of the living mulch. Although less kura clover was maintained in the drought-tolerant corn plots during the growing season, the living mulch's rhizomatous nature should allow it to fully recover after the corn is harvested. The lack of significant differences in grain yields between the living mulch and the killed treatment for the drought-tolerant hybrids suggests that band killing plus broadcast suppression with herbicides is sufficient to reduce competition from the living mulch and maintain high corn yields. We speculate that high yields should be attainable with mechanical mulch suppression strategies, therefore making the system more amenable to organic corn production. Further research is needed on whether kura clover can meet all the N requirements of the drought-tolerant corn.

ACKNOWLEDGMENTS

Cathrine Ziyomo was funded by Project AgGrad, a partnership between the Minnesota Annual Conference of the United Methodist Church and the University of Minnesota. This research was partially supported by the National Institute of Food and Agriculture, USDA, under ID no. WIS01405.

REFERENCES

Abdin, O.A., X.M. Zhou, D. Cloutier, D.C. Coulman, M.A. Faris, and D.L. Smith. 2000. Cover crops and inter-row tillage for weed control in short season maize (*Zea mays*). Eur. J. Agron. 12:93–102. doi:10.1016/S1161-0301(99)00049-0

Affeldt, R.P., K.A. Albrecht, C.M. Boerboom, and E.J. Bures. 2004. Integrating herbicide-resistant corn technology in a kura clover living mulch system. Agron. J. 96:247–251. doi:10.2134/agronj2004.0247

Albrecht, K.A., R.A. Zemenchik, C.M. Boerboom, R.P. Affeldt, and P. Pedersen. 2000. Corn production in a kura clover living mulch. In: Proceedings of the Iowa Forage Conference, Pella, IA. 20–21 Nov. 2000. Iowa Forage and Grassland Council, Des Moines, IA. p. 6–11.

Bänziger, M., F.J. Betrán, and H.R. Lafitte. 1997. Efficiency of high-nitrogen selection environments for improving maize for low-nitrogen target environments. Crop Sci. 37:1103–1109. doi:10.2135/cropsci1997.0011183X003700040012x

Bänziger, M., G.O. Edmeades, D. Beck, and M. Bellon. 2000. Breeding for drought and nitrogen stress tolerance in maize: From theory to practice. CIMMYT, Mexico, DF.

Bänziger, M., G.O. Edmeades, and H.R. Lafitte. 1999. Selection for drought tolerance increases maize yields across a range of nitrogen levels. Crop Sci. 39:1035–1040. doi:10.2135/cropsci1999.0011183X003900040012x

Bard, N.A. 2009. Mechanical and thermal suppression of kura clover living mulch for corn production: An agronomic and biophysical analysis. M.S. thesis. Univ. of Wisconsin, Madison.

Berkevich, R.J. 2008. Kura clover living mulch in cropping systems. M.S. thesis. Univ. of Wisconsin, Madison.

Bernardo, R. 1991. Retrospective index weights used in multiple trait selection in a maize breeding program. Crop Sci. 31:1174–1179. doi:10.2135/cropsci1991.0011183X003100050020x

Betrán, F.J., D. Beck, M. Bänziger, and G.O. Edmeades. 2003. Genetic analysis of inbred and hybrid grain yield under stress and nonstress environments in tropical maize. Crop Sci. 43:807–817. doi:10.2135/cropsci2003.0807

Bolaños, J., and G.O. Edmeades. 1993. Eight cycles of selection for water stress tolerance in lowland tropical maize: I. Responses in grain yield, biomass and radiation utilization. Field Crops Res. 31:233–252. doi:10.1016/0378-4290(93)90064-T

Bosnic, A.C., and C.J. Swanton. 1997. Influence of barnyard grass (*Echinochloa crus-galli*) time of emergence and density on corn (*Zea mays*). Weed Sci. 45:276–282.

Box, J.E., Jr., S.R. Wilkinson, R.N. Dawson, and J. Kozachyn. 1980. Soil water effects on no-till corn production in strip and completely killed mulches. Agron. J. 72:797–802. doi:10.2134/agronj1980.00021962007200050026x

Brown, R.W., G.E. Varvel, and C.A. Shapiro. 1993. Residual effects of interseeded hairy vetch on soil nitrate–nitrogen levels. Soil Sci. Soc. Am. J. 57:121–124. doi:10.2136/sssaj1993.03615995005700010023x

Campos, H., M. Cooper, J.E. Habben, G.O. Edmeades, and J.R. Schussler. 2004. Improving drought tolerance in maize: A view from industry. Field Crops Res. 90:19–34. doi:10.1016/j.fcr.2004.07.003

Costello, M.J., and M.A. Altieri. 1994. Living mulches suppress aphids in broccoli. Calif. Agric. 48:24–28.

De Haan, R.L., C.C. Sheaffer, and D.K. Barnes. 1997. Effect of annual medic smother plants on weed control and yield in corn. Agron. J. 89:813–821. doi:10.2134/agronj1997.00021962008900050016x

Duiker, S.W., and N.L. Hartwig. 2004. Living mulches of legumes in imidazolinone-resistant corn. Agron. J. 96:1021–1028. doi:10.2134/agronj2004.1021

Duvick, D.N. 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). Adv. Agron. 86:83–145. doi:10.1016/S0065-2113(05)86002-X

Edmeades, G.O., J. Bolaños, and S.C. Chapman. 1997. Value of secondary traits in selecting for drought tolerance in tropical maize. In: G.O. Edmeades et al., editors, Developing drought and low N-tolerant maize: Proceedings of a Symposium, , El Batan, Mexico. 25–29 Mar. 1996. CIMMYT, Mexico, DF. p. 222–234.

Edmeades, G.O., J. Bolaños, M. Hernandez, and S. Bello. 1993. Causes for silk delay in a lowland tropical maize population. Crop Sci. 33:1029–1035. doi:10.2135/cropsci1993.0011183X003300050031x

Elkins, D., D. Frederking, R. Marashi, and B. McVay. 1983. Living mulch for no-till corn and soybeans. J. Soil Water Conserv. 38:431–433.

Enache, A.J., and R.D. Ilnicki. 1990. Weed control by subterranean clover (*Trifolium subterraneum*) used as a living mulch. Weed Technol. 4:534–538.

Federer, W.T. 1961. Augmented designs with one-way elimination of heterogeneity. Biometrics 17:447–473. doi:10.2307/2527837

Fleury, D., S. Jefferies, H. Kuchel, and P. Langridge. 2010. Genetic and genomic tools to improve drought tolerance in wheat. J. Exp. Bot. 61:3211–3222. doi:10.1093/jxb/erq152

Gilbert, N. 2010. Food: Inside the hothouses of industry. Nature 466:548–551. doi:10.1038/466548a

Grubinger, V.P., and P.L. Minotti. 1990. Managing white clover living mulch for sweet corn production with partial rototilling. Am. J. Altern. Agric. 5:4–12. doi:10.1017/S0889189300003155

Heyland, K.U., and A. Werner. 1988. The formation of yield and the dynamics of system-conditions in mixed cultivations and their mathematical description with the example of populations consisting of maize and companion plants. Bodenkultur 39:233–250.

Kang, M.S. 1988. A rank-sum method for selecting high-yielding stable corn genotypes. Cereal Res. Commun. 16:113–115.

Kim, B.W. 1996. Kura clover development and performance of kura clover/grass mixtures. Ph.D. diss. Univ. of Wisconsin, Madison.

Lee, M., N. Sharopova, W.D. Beavis, D. Grant, M. Katt, D. Blair, and A. Hallauer. 2002. Expanding the genetic map of maize with the intermated B73 × Mo17 (IBM) population. Plant Mol. Biol. 48:453–461. doi:10.1023/A:1014893521186

Litsinger, J.A., and K. Moody. 1976. Integrated pest management in multiple cropping systems. In: R.I. Papendick, editor, Multiple cropping. ASA Spec. Publ. 27. ASA, CSSA, and SSSA, Madison, WI. p. 239–316.

Ochsner, T.E., K.A. Albrecht, T.W. Schumacher, J.M. Baker, and J. Berkevich. 2010. Water balance and nitrate leaching under corn in kura clover living mulch. Agron. J. 102:1169–1178. doi:10.2134/agronj2009.0523

Ribaut, J.-M., D.A. Hoisington, J.A. Deutsch, C. Jiang, and D. Gonzalez-de-Leon. 1996. Identification of quantitative trait loci under drought conditions in tropical maize: Flowering parameters and the anthesis-silking interval. Theor. Appl. Genet. 92:905–914. doi:10.1007/BF00221905

SAS Institute. 2008. The SAS system for Windows. Release 9.2. SAS Inst., Cary, NC.

Scott, T.W., J. Mt. Pleasant, R.F. Burt, and D.J. Otis. 1987. Contributions of ground cover, dry matter, and nitrogen from intercrops and cover crops in a corn polyculture system. Agron. J. 79:792–798. doi:10.2134/agronj1987.00021962007900050007x

Turner, N.C. 1979. Drought resistance and adaptation to water deficits in crop plants. In: H. Mussell and C.R. Staples, editors, Stress physiology in crop plants. John Wiley & Sons, New York. p. 343–372.

Wall, G.L., W.A. Pringle, and R.W. Sheard. 1991. Intercropping red clover with silage corn for soil erosion control. Can. J. Soil Sci. 71:137–145. doi:10.4141/cjss91-013

Zaidi, P.H., M. Yadav, D.K. Singh, and R.P. Singh. 2008. Relationship between drought and excess moisture tolerance in tropical maize (*Zea mays* L.). Aust. J. Crop Sci. 1:78–96.

Zemenchik, R.A., K.A. Albrecht, C.M. Boerboom, and J.G. Lauer. 2000. Corn production with kura clover as a living mulch. Agron. J. 92:698–705. doi:10.2134/agronj2000.924698x

Ziyomo, C. 2012. Genetic analysis to improve corn grain yield for drought and low nitrogen stress tolerance in a corn–kura clover intercropping system. Ph.D. diss. Univ. of Minnesota, Saint Paul.