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Source: Weed Science, 53(5):709-716.
Published By: Weed Science Society of America
https://doi.org/10.1614/WS04-170R1.1
URL: http://www.bioone.org/doi/full/10.1614/WS04-170R1.1

Weed Science, 53:709–716. 2005

Impact of a terminated wheat cover crop in irrigated corn on atrazine rates and water use efficiency

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A study was conducted near Garden City, KS with irrigated corn to determine how the integration of a terminated winter wheat cover crop with various atrazine rates would affect Palmer amaranth control and corn water use efficiency (WUE). Without atrazine, the presence of a winter wheat cover crop, killed in the boot stage, resulted in a threefold weed biomass reduction in irrigated corn. The highest rate of atrazine completely masked the weed control effect of the cover crop, producing a greater than 15-fold reduction regardless of the presence or absence of the cover crop. A terminated winter wheat cover crop without atrazine elevated corn yield in only two of nine location-yr, and in one instance, depressed yield. However, a terminated wheat cover crop elevated corn yield in six of nine location-yr combinations when used in conjunction with 1.6 kg ha^{-1} atrazine. Although increases in WUE associated with reductions in soil water evaporation produced by the cover crop seemed to be responsible for some of the increase in corn grain yield and stored soil water at the end of the summer growing season, end of season Palmer amaranth biomass had a more profound impact.

Nomenclature: Atrazine; Palmer amaranth, *Amaranthus palmeri* S. Wats., AMAPA; corn, *Zea mays* L. 'DK 592SR'; winter wheat, *Triticum aestivum* L. 'TAM 107'.

Key words: Cover crops, integrated weed management, reduced herbicide rates.

With few exceptions, natural terrestrial ecosystems have a continuous cover of some amount of plant residue on the soil surface. This residue can have profound effects on seedling emergence and succession (Facelli and Pickett 1991). In most agricultural ecosystems, sunlight striking a bare soil surface has two negative impacts. First, it increases nonproductive energy limited evaporation at the expense of the productive transpiration of soil water through the crop (Klocke et al. 1985). Second, it encourages weed seedling recruitment (Teasdale et al. 2003). Therefore, management of plant residue in various tillage strategies and crop production systems is critical for weed management (Buhler et al. 1996; Vidal and Bauman 1996).

Interpretation of cover crop experiments is confounded by an array of non-weed control benefits. Cover crops have long been used to reduce soil erosion and water runoff and to improve water infiltration, soil moisture retention, soil tilth, organic carbon, and nitrogen content (Locke and Bryson 1997; Mallory et al. 1998; Sainju and Singh 1997; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996). Although off-season water is used to grow the cover crop, residual surface residue also can have positive impacts on crop water use during the more critical periods of pollination and grain fill by reducing evaporation (Todd et al. 1991). This winter water use has positive effects on nutrient management that result from controlling off season leaching (Klocke et al. 1999; Varco et al. 1999).

The positive effects of increasing residue by using cover crops are not without costs. Although off season water used by a cover crop has a positive impact in some climates, yield losses associated with water lost growing the cover crop are often found in areas with less than 1000 mm of annual rainfall (Hartwig and Ammon 2002). There is an opportunity cost associated with the water used to grow the cover crop that might otherwise be used to grow the crop to be harvested. Increased residue can affect the movement of herbicide on and into the soil (Banks and Robinson 1986; Crutchfield et al. 1986; Ghadiri et al. 1984; Isensee and Sadeghi 1994; Locke and Bryson 1997; Nagabhushana et al. 2001; Teasdale et al. 2003). Different cover crop systems, like so many other weed control systems, can favor broadleaf, grass, or sedge-type weeds (Reddy 2001, 2003; Reddy et al. 2003; Teasdale et al. 1991). Many studies have shown that cover crop systems alone provide insufficient season-long weed control (Ateh and Doll 1996; Burgos and Talbert 1996; Liebl et al. 1992; Locke and Bryson 1997; Reddy 2001, 2003; Reddy et al. 2003; Teasdale 1996; Yenish et al. 1996). Therefore, it has been concluded in many of these studies that some amount of herbicide input is needed in addition to the cover crop.

The effects of cover crop systems on weed populations have been extensively reviewed (Hartwig and Ammon 2002; Mohler and Teasdale 1993; Teasdale 1998; Williams et al. 1998). The understanding of cover crop systems is confounded by complex interactions. Broad arrays of weed communities compete with each other from season to season. This changing seed rain produces a complex set of species in the weed seed soil bank. The extensive reviews of cover crop systems for weed control suggest that further study is needed to integrate herbicide weed-control systems with cover crop weed control systems and to measure the effects over several yr of repeated treatments, along with their impact on other agronomic factors (Hartwig and Ammon 2002; Teasdale 1998).

To understand the impact of cover crops on weed and crop growth, this study measured the impact of a cover crop on weed control and crop water use while reducing or eliminating the confounding effects of soil type and fertility,

TABLE 1. Location descriptions.

Location	pH	OM	Sand	Silt	Clay	Slope	Standard error	Maximum slope	Minimum slope	Irrigation application rate	Border width	Year[a] of fallow
		%								mm min^{-1}	m	
1	7.0	1.5	30	48	22	0.06	± 0.015	0.075	0.025	1.2	600	1
2	8.3	1.7	26	44	30	0.06	± 0.043	0.16	0.01	1.4	10	1
3	8.3	1.6	30	38	32	0.05	± 0.033	0.10	0.01	1.2	55	2

[a] Yr of fallow preceding the study.

interspecies weed competition, and the movement of herbicide off residues to the soil surface. The objectives of this study were to: (1) measure the impact of three atrazine rates, with and without a terminated winter wheat cover crop, on Palmer amaranth control and corn grain yield; (2) measure the water lost to grow this cover crop; (3) measure the impact of this cover crop residue on growing season water use; and (4) measure the multiple season impacts of repeated imposition of these systems over three yr.

Methods and Materials

Experimental Sites

Sites were selected to minimize the confounding effects of soil fertility and interspecies weed competition on the interactions of the presence or absence of a cover crop with three levels of herbicide. Three sites were selected from within a 53 ha center pivot irrigated field in the summer of 1997 near the Southwest Kansas Research–Extension Center near Garden City, KS. With the exception of management, histories, and beginning weed seed loads, all sites were very similar. The center pivot irrigation system was composed of 7 concentric spans of 41 m each. The soil type was a Richfield silt loam (fine, montmorillonitic, mesic Aridic Argiustoll).

All sites had been used for non-weed control research with aggressive weed management for more than 10 yr before beginning these studies. This resulted in a weed seed soil bank that was predominantly Palmer amaranth and had excess soil fertility. One yr before starting trials at each of the three locations, the entire plot area was moldboard plowed to a depth of 450 mm and maintained weed free for one summer with 0.83 kg ae ha^{-1} applications of glyphosate as needed. To minimize or eliminate the effects of cover crop on soil fertility, sites were selected or amended with excessive levels of soil fertility. Urea fertilizer was applied to deliver 250 kg N ha^{-1} over the entire plot area 10 to 20 d before corn planting each yr. Weather conditions were never favorable for urea volatilization (Ferguson et al. 1984) and past experience has shown that this fertilization rate provides excess nitrogen without harming the corn. Soil phosphate concentrations were in excess of 35 ppm because of regular past applications of cattle manure and phosphate fertilizers during a 30-yr period before initiating these experiments. The soils of this region are naturally high in potassium. All three locations had in excess of 500 ppm K_2O_5.

Location 1 was in the sixth span of the southeastern quadrant of the pivot. This provided it with over 600 m of corn border shielding it from the prevailing south wind. The average wind speed in Garden City, KS is 5.9 m s^{-1} out of the south (Mary Knapp, Kansas weather librarian, personal communication). Wind speed and border width can have a profound influence on water use efficiency (WUE) (Penman 1948). Further, because the outside spans moves faster than the inside spans, the rate of application at a given volume per unit area is faster (Table 1). Although the slopes of all locations were very slight and ranged from 0.049 to 0.055%, location 1 had the least variability in slope. Location 1 treatments began in fall of 1997 and were repeated using the same randomization in the fall of 1998 and 1999 to produce location-yr combinations 1–97, 1–98, and 1–99. Location 1 had been managed for more than 15 yr to conduct entomological or water management experiments.

Location 2 was in the southwestern quadrant of the center pivot in the outside span. Therefore, it had only 10 m of corn border shielding it from the prevailing south wind (Table 1). Location 2 also had the greatest variability in slope. Although all locations were within the same soil type, location 2 had the lowest level of sand. Location 2 treatments began in fall of 1998 with a unique randomization and were repeated in the fall of 1999 and 2000 with this same randomization to produce location-yr combinations 2–98, 2–99, and 2–00. This location had been managed for irrigation experiments for more than 15 yr.

Location 3 was also in the southwestern quadrant of the

TABLE 2. Winter precipitation, summer rainfall, annual precipitation, and departures from 94-yr average for the study (mm).

Year	Winter precipitation		Summer rainfall		Total precipitation		Irrigation	Irrigation and rainfall
	Total	Departure	Total	Departure	Total	Departure		
	mm							
1997–1998	205	16	337	62	542	79	254	796
1998–1999	268	80	350	74	618	154	305	923
1999–2000	241	52	200	−76	441	−23	330	771
2000–2001	195	7	378	102	573	110	279	852
2001–2002	85	−104	169	−106	255	−209	216	471
Normal	189		276		464			

Table 3. Effects of a terminated winter wheat cover crop with three levels of atrazine on mid June Palmer amaranth biomass as indexed by the product of weed height (cm) and weed number m^{-2}.

Atrazine rate	Winter wheat cover crop	
	Present	Absent
$kg\ ha^{-1}$	Plant height (cm) × weed # m^{-2}	
0	27.2	83.1
0.8	3.8	4.3
1.6	1.8	1.8
LSD (P = 0.05)	32.8	

center pivot but because it was in the sixth span it had 55 m of corn border protecting it from the prevailing south wind. With the exception of pH and presumed beginning weed seed load, location 3 was similar to location 1 in all other respects. Unlike the other two locations, it was fallowed an extra yr prior to initiation with 0.83 kg ha^{-1} of glyphosate in the summers of 1997 and 1998. It is assumed that this untilled fallow period reduced the beginning weed seed soil bank and increased beginning soil water content. Location 3 treatments began in fall of 1999 with a unique randomization and repeated in the fall of 2000 and 2001 with this same randomization to produce location-yr combinations 3–99, 3–00, and 3–01. It had been managed for bulk crop production for more than 15 yr.

With the exception of 1999, when location 1 was treated the third time, location 2 was treated the second time, and location 3 was treated for the first time, most site location-yr combinations were grown in 5 different seasons with very different rainfall patterns. Because of extraordinary drought conditions during the summer of 2002 (Table 2), water demands exceeded capacity of the well such that location-yr 3–02 could not be fully irrigated as described for other locations-yr.

The relationship of weed seed soil bank numbers to final weed populations is often weak (Ball and Miller 1989; Roberts 1958, 1981; Wilson et al. 1985), often less than 10% of an amaranth spp. seed soil bank germinates in a given yr (Ball and Miller 1989). However, Massinga et al. (2001) showed that different densities and times of emergence of Palmer amaranth could produce a greater than fivefold difference in end season seed rain. A broad range of final weed biomass was produced in the first yr of treatment at each location. One can conclude from the work of others, done near these locations (Massinga et al. 2001), that this produced different levels of Palmer amaranth seed rain. Due to reimposition of treatments on plot areas in successive yr in any given yr, all location-yr combinations could have had very different weed seed soil banks.

Cover Crop Establishment and Water Use

In the first week of October of each location-yr, the winter wheat 'Tam 107' was drilled in 9 by 14 m plots at 100 kg ha^{-1} in 3 of 6 plots in each of 5 blocks. This relatively high seeding rate was used to ensure maximum residue and minimize within plot stand variation. Regardless of the presence or absence of cover, all plots were irrigated with 25 mm of water within 1 d of planting to ensure uniform wheat emergence.

The opportunity cost of water lost by growing the winter wheat cover crop was determined by gravimetrically measuring soil moisture to a depth of 1.5 m, 7 to 18 d after wheat emergence as described by Kohnke (1968). This procedure was repeated 7 to 10 d after corn emergence. The water cost of growing the cover crop was determined by subtracting the former soil moisture value from the latter. It was assumed that water lost to leaching below the corn root zone was minimal based on irrigation modeling work done previously with similar soils near these locations (Massinga et al. 2003; Rogers et al. 2002; Trooien et al. 1999).

Corn Establishment

When wheat reached boot stage, or approximately the first week in May, 0.83 kg ha^{-1} of glyphosate was applied to the entire plot area to kill the wheat and any weeds that were present in the noncover crop plots. Winter annual weeds were less than 5 cm tall and their densities were much less than one plant per 10 m^2.

Sethoxydim-resistant corn cultivar DK 592 SR was planted at a density of 75,000 plants ha^{-1} in 76 cm rows at a depth of 2.5 cm with a no-till planter. Atrazine was applied at 0, 0.8, or 1.6 kg ha^{-1} to produce a balanced factorial arrangement of treatments with two densities of cover and three rates of atrazine. A blanket irrigation of 25 mm was then applied to ensure uniform corn emergence, and move atrazine off plant residues and incorporate it into the soil surface (Ghadiri et al. 1984).

The entire plot area was treated with 0.3 kg ai ha^{-1} of sethoxydim as needed to remove light and nonuniform infestations of grassy weeds. To further increase uniformity, all weeds other than Palmer amaranth were removed manually. Weed and corn heights were measured in mid June and the density of each per m^2 was counted. Many treatments produced so few weeds that destructive sampling was not possible. Therefore, an index of Palmer amaranth biomass

Table 4. Atrazine effect on Palmer amaranth biomass at corn harvest averaged over terminated wheat cover crop at each location-year.

Atrazine rate	Palmer amaranth biomass								
	Location 1			Location 2			Location 3		
	1998	1999	2000	1999	2000	2001	2000	2001	2002
$kg\ ha^{-1}$	$kg\ ha^{-1}$								
0	9619	4093	2381	3936	2002	5893	318	8810	5897
0.8	884	2240	2029	2020	1394	6369	686	7084	6714
1.6	525	1509	1518	1484	1018	5298	225	6191	6808
LSD (P = 0.05)	1547	1551	611	1443	649	ns[a]	ns	1962	ns

[a] Abbreviation: ns, not significant.

TABLE 5. Effect of terminated winter wheat cover crop on Palmer amaranth biomass at corn harvest averaged over atrazine rates for each location-yr.

Winter wheat cover crop	Palmer amaranth biomass								
	Location 1			Location 2			Location 3		
	1998	1999	2000	1999	2000	2001	2000	2001	2002
	kg ha^{-1}								
Present	3301	1946	1885	2060	1434	5715	577	6032	6031
Absent	3800	3281	2067	2900	1508	5992	242	8691	6914
LSD (P = 0.05)	ns[a]	1267	ns	ns	ns	ns	ns	1602	ns

[a] Abbreviation: ns, not significant.

was estimated by multiplying density and height values. This index has been used effectively when destructive samples are not practical (Currie and Thompson 2000). Weed biomass was only determined at corn harvest. When corn grain moisture dropped below 18%, it was harvested and yield was adjusted to 15.5% moisture.

Water Management

When the corn had 2 to 4 leaf collars, aluminum access tubes were installed to measure volumetric soil water content with the neutron attenuation method as described by Stone et al. (1955). Soil water was measured in 30-cm increments to a depth of 1.5 m approximately every 14 d. Center pivot sprinkler irrigation of corn began in the late vegetative stage when total soil moisture in the driest treatment reached 50% of field capacity to a depth of 1.5 m. This occurred within 7 to 10 d of corn tasseling and approximates when a producer with a limited well size would begin irrigation to ensure maximal pollination. After that point, 25 mm of water was applied with a center pivot sprinkler system every 6 d to simulate what a producer in this area could apply with a modest size 2460 L min^{-1} well serving a 53-ha field. Irrigation was terminated when sufficient stored soil moisture was present to complete corn development based on irrigation models for this region (Rogers et al. 2002). This occurred when the corn was at about the late dent stage of development.

Evapotranspiration (ET) was calculated with a soil water balance from the equation

$$ET = I + R + \Delta S - D, \qquad [1]$$

where ET = evapotranspiration in mm during measurement period; I = net irrigation in mm; R = precipitation in mm; ΔS = the difference in soil water in mm in 1.5 m of soil from the beginning to the end of the measurement period; and D = water drainage in mm below the 1.5 m rooting depth. Although drainage below 1.5 m cannot be ruled out, it was assumed to be negligible during the measurement periods based on the magnitude in change of volumetric soil water content of the lower two depths and comparisons with drainage models for similar soils. Summer season ET was summed from the biweekly measurement periods. WUE was calculated by dividing corn grain yields by growing season ET of the corn crop.

To measure the impact of repeated use of these systems, the entire plot area was disked twice shortly after corn harvest and the treatments were reapplied on the same plots for two more seasons at each of the three locations. This produced a total of nine location-yr combinations.

TABLE 6. Effects of a terminated winter wheat cover crop on corn grain yield with three levels of atrazine.

	Corn grain yield					
Location 1	1998		1999		2000	
	Cover crop					
Atrazine rate	Absent	Present	Absent	Present	Absent	Present
kg ha^{-1}	kg ha^{-1}					
0	2440	4520	3990	6020	2450	3090
0.8	6020	6920	5080	6260	3650	3820
1.6	6940	6890	5660	6950	3470	4045
LSD (P = 0.05)	920		1140		1070	
Location 2	1999		2000		2001	
0	4040	4870	2430	2560	1280	2390
0.8	4530	5330	2370	3210	1410	2490
1.6	4150	5810	2460	3260	1530	2880
LSD (P = 0.05)	1350		1200		1280	
Location 3	2000		2001		2002	
0	5160	4630	1380	2460	320	330
0.8	5100	5020	2070	3970	200	580
1.6	5140	5320	3150	3860	360	720
LSD (P = 0.05)	890		1540		640	

TABLE 7. Difference in stored soil water in 1.5 m of soil profile from fall to spring in a terminated winter wheat cover crop.

Winter wheat cover crop	Stored soil water								
	Location 1			Location 2			Location 3		
	1998	1999	2000	1999	2000	2001	2000	2001	2002
	mm of soil water								
Present	−5[a]	−76	58	−5	19	69	−56	66	−48
Absent	81	66	175	23	86	79	18	61	−51
LSD (P = 0.05)	50	24	34	ns[b]	35	ns	39	ns	ns

[a] Positive numbers indicate water accumulation; negative numbers indicate water usage.
[b] Abbreviation: ns, not significant.

Statistical Analysis

Plots were arranged in a randomized complete block design with five replications. All data were subjected to analysis variance using PROC ANOVA[1] to determine all interactions of location, amount of cover, and herbicide rate. All data were pooled across factors if the interactions were not significant at the 5% level. Means were then separated by using Fisher's protected LSD ($P < 0.05$). Although space constraints and financial considerations did not allow the inclusion of a weed-free control to allow the measurement of the terminated wheat cover crop independent of the effects of Palmer amaranth, multiple regression analysis was performed to measure the relative impact of these factors within the models. All permutations of herbicide rate, wheat biomass, final Palmer amaranth biomass, and the squares and cubes of these factors were regressed against corn yield, WUE, and ET using the PROC R-SQUARE[1] procedure. All intercepts and parameters were *t*-tested for statistical significance ($P < 0.10$).

Results and Discussion

Rainfall and Irrigation

Data for annual precipitation received during the study period were recorded from the National Weather Service station number 14–2980–7, which was within 600 to 900 m of the field sites. Precipitation reporting was divided into the winter and summer growing seasons, corresponding to the growing seasons of the winter wheat (September–May) and the corn crop (May–August), respectively. Departures from normal precipitation recorded from 1908 through 2002 were also calculated (Table 2).

Rainfall information was collected at the field sites during the summer growing season and recorded along with total irrigation for the growing season (Table 2). Growing season totals of irrigation and rainfall were the bulk of the contribution to evapotranspiration or the consumptive use for irrigated crops. Change in soil water content from the beginning of the season to the end contributed positively or negatively to ET.

Weed Effects

Early season weed density and weed height was highly variable and difficult to interpret (data not shown). However, by mid June the product of Palmer amaranth height and plant number m^2 proved to be a reproducible weed index (Table 3) which yielded no location by yr interaction. This reduction in variability is consistent with work done in other weed species (Currie and Thompson 2000). The presence of the wheat cover crop alone in the absence of atrazine resulted in a threefold reduction in weed biomass compared to treatments with no cover. However, all rates of atrazine completely masked the cover crop effect producing a 15- to 46-fold reduction in weed biomass, regardless of presence or absence of the wheat cover crop. Weed control was similar when atrazine was applied at either rate, although 100% weed control was achieved in 2 of 9 location-yr with the highest rate of atrazine plus the cover crop (data not shown).

The 0.8 kg ha^{-1} atrazine treatment reduced end-of-season Palmer amaranth biomass in 3 of 9 location-yr (Table 4). In contrast, the 1.6 kg ha^{-1} atrazine treatment reduced end-of-season Palmer amaranth biomass in 6 of 9 location-yr.

The response of end-of-season Palmer amaranth biomass to cover was more variable (Table 5) with differences significant in 2 of 9 location-yr. The inability of the cover crop to supply season-long control is consistent with the reports of many researchers (Ateh and Doll 1996; Burgos and Talbert 1996; Liebl et al. 1992; Locke and Bryson 1997; Reddy 2001, 2003; Reddy et al. 2003; Teasdale 1996; Yenish et al.

TABLE 8. Impact of prior seasons' atrazine use on terminated winter wheat cover crop dry matter production.

Atrazine rate	Wheat cover crop dry matter								
	Location 1			Location 2			Location 3		
	1998	1999	2000	1999	2000	2001	2000	2001	2002
kg ha^{-1}	kg ha^{-1}								
0	1469[a]	1506	588	1322[a]	661	441	1139[a]	808	147
0.8	—	1763	808	—	771	882	—	698	294
1.6	—	1653	882	—	624	661	—	808	220
LSD (P = 0.05)	—	ns[b]	ns	—	ns	222	—	ns	133

[a] An average of 15 plots because atrazine treatments were not applied at this point in the experiment.
[b] Abbreviation: ns, not significant.

Table 9. Difference in stored soil water in 1.5 m of soil profile from spring to fall produced by corn growing in a terminated winter wheat cover crop.

Winter wheat cover crop	Soil water change								
	Location 1			Location 2			Location 3		
	1998	1999	2000	1999	2000	2001	2000	2001	2002
	mm of soil water								
Present	3[a]	1	−5	10	5	−66	−46	−66	33
Absent	−61	−71	−64	−86	−24	−91	−61	−122	1
LSD (P = 0.05)	18	15	16	54	16	23	ns[b]	54	24

[a] Positive numbers indicate water accumulation; negative numbers indicate water usage.
[b] Abbreviation: ns, not significant.

1996). It is possible that the more favorable soil moisture conditions produced by the wheat cover crop later in the season allowed Palmer amaranth to compensate for early season stunting.

Corn height at tassel was the most reproducible index of crop injury. The presence of cover reduced corn height at tassel, 7.4 cm (± 4.8 cm LSD P = 0.05). Stewart et al. (1975) and Barrett and Skgogerboe (1978) reported that water stress during corn vegetative growth was not necessarily detrimental to crop yield. They suggested this stress allowed for some conditioning of the plant to later water stress. It was assumed that the corn stunting measured in our study was due to water stress induced by wheat cover crop and Palmer amaranth water use, but allelopathic effects of wheat residue or weeds could not be ruled out.

Cover and herbicide rate and location-yr impacted corn yield in a three way interaction. Despite corn stunting measured in the cover crop treatments in the absence of atrazine, no depression of corn grain yields were measured compared to the no cover treatments. However, the presence of a cover crop only elevated corn grain yield in 2 of 9 location-yr (Table 6). In the absence of a cover crop, atrazine at 0.8 or 1.6 kg ha^{-1} increased yield over the control in 3 of 9 location-yr. Cover crop seemed to positively interact with atrazine. Atrazine plus cover increased yield over the control in 4 of 9 location yr with the 0.8 kg ha^{-1} treatment and 6 of 9 location yr with the 1.6 kg ha^{-1} treatment. The yield increase was due to a consistency in early season weed control when atrazine was applied with the cover crop (Table 6). Early season Palmer amaranth competition reduces corn grain yield more than it does later in the season (Massinga et al. 2001). Although the wheat cover crop did not provide season long weed control, it seemed to enhance atrazine treatments during this more critical early period.

Cover Crop and Soil Water Effect

Winter wheat biomass varied among the location-yr combinations producing significant location-yr by cover and location-yr by herbicide rate interactions. The gain or loss in soil water during the winter growing season represented the investment in water for growing the terminated cover crop that might, or might not, be compensated for later through more efficient water use in the corn crop. In 4 of the 9 location-yr, there was no difference in soil water accumulation in the 1.5-m soil profile between the cover and no-cover plots. In 5 of the 9 location-yr, the difference ranged from 68 to 142 mm with more water accumulated in no cover crop treatment (Table 7).

Dry matter production followed the winter accumulation of soil water in winter wheat (Table 8). The beginning yr for each location followed fallow plots, leading to more stored soil water in the initial yr of each location than in subsequent yr (Table 7). These initial location-yr, plus location-yr 1–99, produced the most wheat biomass. These four location-yr also produced all of the winter soil water depletion for the cover treatment, except for location-yr 3–02, which was the driest of the study (Table 7). No atrazine was applied the yr prior to initiation of each location. However, in the second and third repetition at each location, a potential existed for atrazine to injure wheat. However, no injury was ever observed and total dry matter was never reduced, and in two location-yr it was elevated by prior atrazine use.

The no-cover treatment consistently accumulated more soil water than the cover treatment during the winter (Table 7) and depleted it more during the summer (Table 9), except in the driest location-yr, 3–02. The difference ranged from 39 to 87 mm in the 1.5-m soil profile. In the single loca-

Table 10. Corn evapotranspiration with and without a terminated winter wheat cover crop during the summer growing season.

Winter wheat cover crop	Evapotranspiration								
	Location 1			Location 2			Location 3		
	1998	1999	2000	1999	2000	2001	2000	2001	2002
	water use mm[a]								
Present	521	533	412	566	406	412	465	412	625
Absent	584	533	443	625	445	499	495	498	589
LSD (P = 0.05)	22	ns[b]	ns	46	24	46	ns	46	ns

[a] Evapotranspiration = soil water evaporation + plant transpiration.
[b] Abbreviation: ns, not significant.

Table 11. Water use efficiency (WUE) of corn grown with and without a terminated winter wheat cover crop.

Winter wheat cover crop	Water use efficiency								
	Location 1			Location 2			Location 3		
	1998	1999	2000	1999	2000	2001	2000	2001	2002
	kg-ha^{-1} mm^{-1}								
Present	11.8	9.2	9.2	9.7	7.6	6.5	12.4	8.4	0.8
Absent	8.8	12.2	7.4	6.9	5.5	2.9	16.8	4.6	0.5
LSD (P = 0.05)	1.2	2.2	ns[a]	1.8	2.0	2.4	1.7	2.5	ns

[a] Abbreviation: ns, not significant.

tion-yr (3–02) when the trend was reversed, the crop and weeds were severely water stressed by the second driest yr in 94 yr of recorded weather.

Among the location-yr combinations, ET produced significant location-yr by cover and location-yr by herbicide rate interactions. However, the level of cover did not interact with herbicide rate within a given location-yr combination, presence of the cover crop never increased ET, and reduced it in 5 of 9 location-yr (Table 10). WUE in the presence of the cover crop was greater than in the absence of the cover crop in 5 of 9 location-yr (Table 11).

The gain or loss of soil water during the fall and winter months, as well as during spring crop growth, had profound effects on corn yield. Growing a wheat cover crop used water that otherwise would have been available for corn growth in slightly more than half of location-yr, with a water opportunity cost of 68 to 142 mm for growing the cover crop. However, these winter season losses were offset by gains in summer growing season WUE produced by the cover. Cover crop treatments lost less water to nonproductive evaporation in 5 of 9 location-yr (Table 10).

Less soil water at the end of the corn growing season (Table 9) along with more ET in the no cover treatment indicated that more soil evaporation was taking place. Todd et al. (1991) reported and Klocke (2003) confirmed a similar response with post harvest wheat residue. The terminated cover crop residue reduced energy limited soil water evaporation and made the saved water available for transpiration, possible yield increases, or residual stored soil water.

We assume that the lower yields associated with location 2 were due to its inherently lower WUE. Only preplanned comparisons should be made and interactions of cover and herbicide should not allow the averaging of effects. However, in the three yr that tests were conducted at location 2, all other locations had from 1.7 to 2.4 kg ha^{-1} mm^{-1} greater WUE (data not shown). This lower WUE was attributed in varying degrees to edaphic and microclimate effects. It is assumed that location 2 had a less uniform water intake due to its higher variability in slope and lower sand content (Table 1). The effect of this reduced water intake was further exacerbated by a higher irrigation application rate (Table 1) and that caused more water to run off or be more unevenly distributed within the plots or both. The slopes of these plots are extremely modest in comparison to many major corn growing regions of the world. In addition, there was increased evaporation due the relative proximity of each location to the prevailing wind (Penman 1948). All these factors might have led to an overall lower WUE for location 2.

In spite of the opportunity cost of water lost to grow the cover crop, WUE was improved through the use of the wheat cover crop (Table 11). Although the design of these experiments did not allow a direct comparison of the interaction of Palmer amaranth end of season biomass and winter wheat cover crop biomass, regression analysis provided a modest means of partitioning the impact of Palmer amaranth biomass and wheat cover crop biomass. Out of the 31 total possible permutations of regression models, only two models had intercepts and parameter estimates that were significant at $P \leq 0.10$. In both models, intercepts and all pigweed parameters were significant at $P < 0.01$. Palmer amaranth biomass (PAB) at the end of the season predicted 47% of the variation in WUE:

$$\mathrm{WUE} = 1.16 - \mathrm{PAB}(0.001); \qquad r^2 = 0.47 \qquad [2]$$

Although Massinga et al. (2003) models were much more predictive, often producing R^2 values greater than 0.95, they used Palmer amaranth density, not end-of-season Palmer amaranth biomass. Further, their models were only useful at populations of less than four plants per m of row. The populations in these studies were 10- to 100-fold denser. Further, their models showed very little decrease in WUE with successive increases in population from six to eight Palmer amaranth plants per m of row. Therefore, the higher populations observed in this study are representative of the upper limits of their model and tend to substantiate their work.

The addition of the square of the Palmer amaranth biomass (PAB^2) and the wheat cover crop biomass (WCCB) provided a modest improvement in the predictive power of the model:

$$\mathrm{WUE} = 12.3 - \mathrm{PAB}(0.0022) + \mathrm{PAB}^2(0.00000014) + \mathrm{WCCB}(0.00022); \qquad R^2 = 0.56 \qquad [3]$$

The significance of PAB^2 tends to support the curvilinear nature of Massinga et al. (2003) models. The WCCB parameter estimate was significant at $P = 0.07$. These models have extremely limited utility at predicting WUE under limited irrigation and high Palmer amaranth population, although they are in substantial agreement with the work of others and show differences in relationships and magnitudes among the factors. Palmer amaranth biomass had a negative impact that was 10-fold larger than the positive impact of the wheat cover crop biomass.

Sources of Materials

[1] SAS Software® Statistical Analysis Systems, SAS Campus Drive, Cary, NC 27511.

Acknowledgment

This is Contribution Number 04-324-J of the Kansas Agricultural Experiment Station, Manhattan, Kansas.

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Received September 29, 2004, and approved May 27, 2005.