Use of a mechanical roller-crimper as an alternative kill method for cover crops

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Abstract. *Cover crops have long been recognized as a beneficial component of many cropping systems; however, their use is still not commonplace. Usage may be increased by identifying more cost-effective and environment-friendly techniques for cover-crop management. This study was conducted to determine the effectiveness of using a mechanical roller-crimper as an alternative method for killing cover crops. The study location was in east-central Alabama, using a split-split plot experimental design with four replications and 3 site-years during 1999–2000. Rye, wheat and black oat were evaluated in terms of ease of kill and optimum time of kill using a roller-crimper, two herbicides (paraquat and glyphosate) at their labeled rate, and two reduced chemical (half label rate) combinations of the same chemicals with the roller-crimper. Four Feekes' scale growth stages were used to determine optimum time of kill; 8.0 (flag leaf), 10.51 (anthesis), 10.54 (early milk) and 11.2 (soft dough). Plant growth stage was the main determining factor for effectiveness of the roller-crimper for killing the cover crops. At the flag leaf stage, the roller-crimper provided only 19% kill across all covers over the 3 site-years. After plants reached anthesis, the roller-crimper with half-rate herbicide combinations equaled the effectiveness of herbicides alone at their label rate, averaging 94% kill. By the soft dough growth stage, all kill methods were equally effective due to accelerating plant senescence (95% mean kill across kill methods). Use of the roller-crimper alone after anthesis can decrease costs by as much as $26.28 per ha, while providing a kill rate equivalent to that of herbicide treatment alone.*

Key words: *Avena strigosa* Schreb., C:N ratio, conservation tillage, growth stage, glyphosate, paraquat, *Secale cereale* L., *Triticum aestivum* L.

Introduction

Cover-crop use has increased among growers in the US due to increased awareness of their benefits and greater focus on conservation (Sustainable Agriculture Network, 1998). Cover crops reduce nitrate leaching, reduce soil erosion, improve soil fertility, increase soil water infiltration and storage, and suppress weeds (Blevins et al., 1971; Dinnes et al., 2002; Doran and Smith, 1991; Kaspar et al., 2001; Munawar et al., 1990; Nagabhushana et al., 2001; Reeves, 1994). Small-grain cereals are often used as cover crops; they are adapted to many geographic areas and cropping systems and can be economically less risky than legume cover crops (Sustainable Agriculture Network, 1998; Wilkins and Bellinder, 1996). Cereals have high carbon to nitrogen ratios (C:N ratio) and high cellulose and lignin contents, which is beneficial in that residues decompose more slowly than legume residues (Morse, 1998; Munawar et al., 1990; Ranells and Wagger, 1996; Wagger, 1989). Wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.) are commonly used cover crops in many areas of the US (Wilkins and Bellinder, 1996). Black oat (*Avena strigosa* Schreb.) is a cover crop widely used in Brazil (Derpsch et al., 1991) and has been introduced recently for use in the south-eastern US (Bauer and Reeves, 1999; Patterson et al., 1996; Reeves et al., 1997). Patterson et al. (1996) found that black oat matures faster than wheat and rye in warm climates and also produces a significant amount of plant biomass. Black oat has also been shown to have allelopathic properties, with the potential to control both annual grasses and some small-seeded broadleaf weeds (Bauer and Reeves, 1999; Derpsch, 1990; Patterson et al., 1996; Reeves et al., 1997). However, it has been identified as having low tolerance to temperatures less than –7°C (depending on growth stage), which may be a disadvantage by limiting the range of adaptation (Bauer and Reeves, 1999; Reeves et al., 1997).

Traditionally, cover crops have been terminated using non-selective, post-emergence contact or systemic herbicides, usually paraquat (1,1′-dimethyl–4,4′-bipyridinium) or glyphosate [*N*-(phosphonomethyl) glycine] (Anderson, 1996; Munawar et al., 1990; Weston, 1990). Both of these chemicals are effective on small-grain cereal cover-crop species (Munawar et al., 1990; Weston, 1990). Chemical

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desiccation of cover crops is highly effective and can be relatively quick, depending on the herbicide, so it is an attractive option for farmers.

However, herbicide cost is a disadvantage of this termination method and can comprise a large portion of a farmer's annual expenses (Kelly et al., 1996; Wilkins and Bellinder, 1996). In addition, there is increased concern over the use of all agricultural chemicals. Specifically, the possibility of surface and groundwater contamination (Kookana and Aylmore, 1994; Ritter, 1990), soil contamination (Kookana et al., 1995) and the potential for increased incidence of weed resistance to herbicides (Holt et al., 1993; Powles et al., 1997) have caused concern among the general public and agricultural communities. These concerns, along with increasing input costs, provide incentive for researching alternative methods to terminate cover crops.

Mechanical kill methods may serve as an alternative to herbicides. These methods might also be used in combination with herbicides to reduce the chemical rate required for kill. Mowing, rolling/slicing with coulters, and undercutting are mechanical kill methods that have been used and evaluated on a limited basis in the US (Creamer et al., 1995; Dabney et al., 1991; Hoffman et al., 1993; Morse, 1998; Wilkins and Bellinder, 1996). Dabney et al. (1991) used vertical coulters spaced 10 or 20 cm apart to chop several legume cover crops, followed by atrazine application 14 days later. Kill ratings ranged from 16 to 99%, dependent on legume species, coulter spacing and growth stage of the legumes. Hoffman et al. (1993) reported that chopping with a roller was no more effective than a no-till planter in killing hairy vetch (*Vicia villosa* Roth). Undercutters are not practical for no-tillage systems and mowers require energy-intensive power take-off (PTO)-driven equipment. Rolling drums fitted with blades (referred to as *rolo-faca* in Portuguese) have been used for many years in southern Brazil and Paraguay to terminate cover crops and facilitate planting in conservation tillage systems (Derpsch et al., 1991). Typically, the blades are dull and are designed to crush or crimp cover-crop stems, rather than cut or chop them. Energy requirements for a roller-crimper can be estimated from that required by a land roller or cultipacker (0.7–2.4 kW·h ha^{-1}). This is tenfold less than the energy requirement of a rotary mower (9.2–24 kW·h ha^{-1}) (Hunt, 1977). Roller-crimpers can be especially useful in conservation tillage systems, as the roller-crimper provides a unidirectional residue mat, facilitating planting operations and improving seed–soil contact and plant emergence. The use of the roller-crimper as a kill method is new to US growers, therefore more research is necessary before it will be widely accepted.

Timing of kill is also a very important component in cover-crop management, especially with the use of mechanical kill methods (Creamer et al., 1995; Munawar et al., 1990). Some researchers have noted that growth stage of a cover crop affects the ease of mechanical kill (Creamer et al., 1995; Morse, 1998). Creamer et al. (1995) showed killing cover crops of rye, hairy vetch (*Vicia villosa* L.), crimson clover (*Trifolium incarnatum* L.) and barley (*Hordeum vulgare* L.) with an undercutter to be easiest and most effective (95% kill or higher) when the cover crops were at mid- to late-bloom or later. However, many farmers determine kill time based on planting date of the cash crop, e.g., 2–4 weeks prior to cash-crop planting date, rather than at a certain growth stage. Further investigation is required to establish growth-stage-based cover-crop termination as common practice.

The objectives of this study were threefold: (1) determine the effectiveness of using a roller-crimper compared to, or in addition to, herbicides as a cover-crop kill method; (2) determine the optimum kill time for black oat, rye and wheat cover crops, using easily identified stages of the Feekes' scale (Large, 1954); and (3) identify any differences in ease of kill for these three cover crops using the roller-crimper.

Methods and Materials

The study was conducted at two locations in east-central Alabama during 1999 and one location in 2000, providing 3 site-years of data. For this location, the average frost-free growing season is 220 days and annual rainfall is 1425 mm, normally distributed throughout the year. The average annual temperature is 17.2°C, with mild winter temperatures (December–February mean temperature is 7.9°C; mean minimum temperature is 1.6°C, with an average of 29 days occurrence of temperatures <0°C during this period). The soil types (sites) in 1999 were a Compass loamy sand (coarse-loamy, siliceous, subactive, thermic Plinthic Paleudults) and a Cahaba sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Hapludults). In 2000, the experiment was conducted on the Compass sandy loam site. A split-split plot experimental design with four replications was used at each site-year. Whole plots were three small-grain cover crops: 'Elbon' rye, 'Coker 9803' wheat, and 'SoilSaver' black oat. Cover crops were planted at a rate of 100 kg ha^{-1} on 18 November 1998 and 9 November 1999, using a grain drill with double-disk openers. Sixty-three kg N ha^{-1} was applied as ammonium nitrate each season. Plots were 2.4 m wide and 7.6 m long. During the first year of data collection (1999), three easily identifiable growth stages using the Feekes' scale were subplots: Feekes' Scale 8 (flag leaf), 10.51 (anthesis) and 11.2 (soft dough). In 2000, the early milk growth stage (Feekes' Scale 10.54) was evaluated as the last growth stage, replacing the soft dough growth stage. Sub-subplots were five kill methods: roller-crimper only, glyphosate at 1.68 kg ai ha^{-1} (label rate), paraquat at 0.69 kg ai ha^{-1} (label rate), roller-crimper + glyphosate at 0.84 kg ai ha^{-1} (half label rate), and roller-crimper + paraquat at 0.35 kg ai ha^{-1} (half label rate). Since efficacy of label rates was validated by extensive data prior to registration of herbicides, we did not include half label rate glyphosate and paraquat treatments without use of the roller-crimper.

The roller-crimper used was a drum roller with horizontal welded blunt steel metal strips, which crushed and crimped cover crop stems without cutting them. The roller-crimper drum was 2.4 m wide with a diameter of 406 mm, with seven blunt steel blades (76 mm height) placed 76 mm apart around the drum separated by inverted angle-irons with 54 mm height (Fig. 1).

All cover crops were monitored regularly to determine growth stage. Kill treatment was applied when at least 65% of the plot was at the desired growth stage. At each stage, prior to kill treatment, two 0.25 m^2 biomass samples within each subplot were obtained to determine biomass production and C:N ratio. Biomass samples were oven-dried at 65°C to a constant weight.

Percent kill measurements were taken at 7, 14, 21 and 28 days after treatment, using both a visual rating method and plant moisture content samples. Visual measurements were made using a 0–10 scale, with 0 being no kill and 10 being complete kill. Data were expressed as percentage kill by multiplying the rating by 10. Data from 28 days are presented as they best correlated with plant moisture results; although it should be noted that there was no significant difference in visually rated percentage kill at 14 versus 28 days after treatment. In conservation tillage systems, terminating covers 4 weeks prior to planting the cash crop is a standard recommendation in order to minimize potential stand problems as a result of soil water depletion, allelopathy and disease.

Gravimetric soil water content measurements were taken 28 days after treatment to determine the amount of soil water available to a cash crop. Soil water is an important consideration in cover-crop management, since creation of a water deficit by a cover crop can be a problem for the cash crop, especially in a year with low spring rainfall (Munawar et al., 1990; Reeves, 1994; Williams et al., 2000). Soil samples were taken in the top 7.6 cm of soil (cash-crop seed zone) in each sub-subplot. Samples were weighed, oven dried at 105°C, then weighed again and water content measured by difference (Gardner, 1986). Weed biomass measurements (two 0.25 m^2 per sub-subplot) were also taken 28 days after treatment to evaluate kill methods and cover crops in terms of weed control.

All data were analyzed for main effects and interactions using analysis of variance (ANOVA) (SAS Institute, 1988). Fischer's protected least significant difference (LSD) was used for mean separations. For all data, an *a priori* $P \leqslant 0.10$

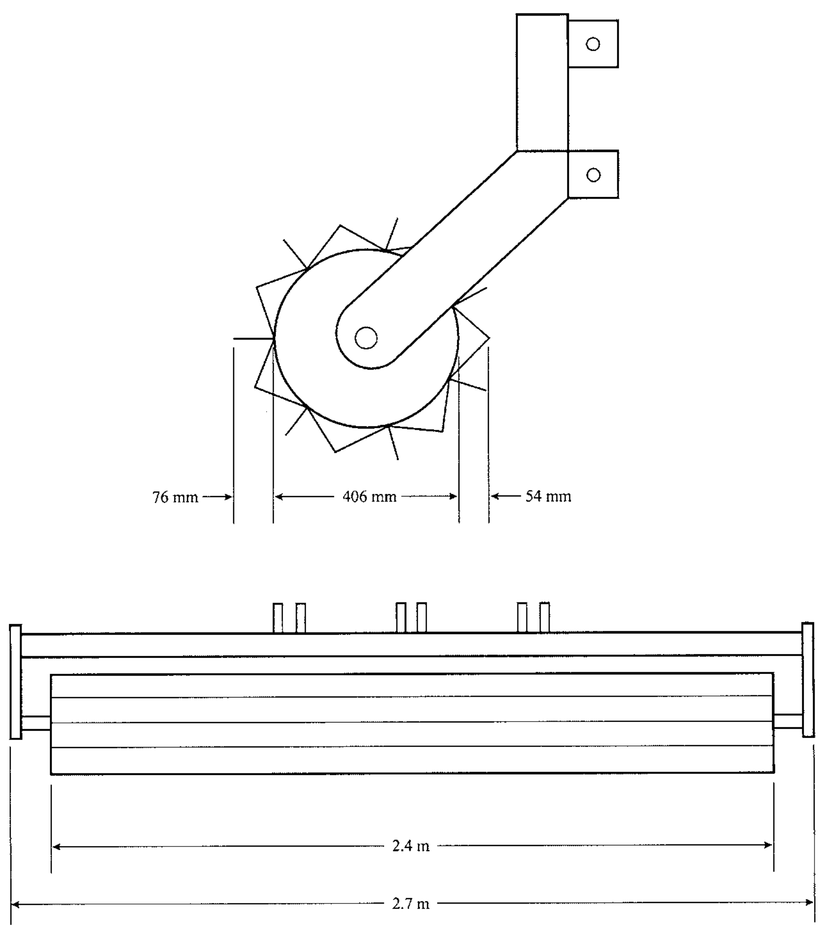

Figure 1. Schematic drawing of the roller-crimper used in this project. Inverted angle iron between blades dampens vibration and reduces blades cutting into soil.

significance was used. No significant site interactions were observed for cover-crop biomass, percent kill or soil water content, therefore these data for the 1999 season are presented averaged over both sites. Significant site interactions for weed biomass and cover-crop C:N ratio were observed, and these data were analyzed and are presented separately by site for 1999. Simple linear regression and correlation analysis were performed to establish relationships between variables.

Results and Discussion

Cover-crop biomass production

In 1999, a significant cover crop × growth stage interaction occurred for cover-crop biomass (Table 1). Rye and wheat biomass increased significantly through the soft dough growth stage; maximum biomass for rye and wheat at soft dough were 9.5 and 10.5 Mg ha^{-1}, respectively. However, black oat reached maximum biomass of 8.6 Mg ha^{-1} at anthesis. Attaining maximum biomass at an earlier growth stage may be beneficial, as it would allow greater residue production at an earlier planting date for a cash crop. Biomass production by black oat was significantly lower than that of rye and wheat in 1999. This is likely the result of extreme and unusually low temperatures during early development of the crop; early January temperatures were as low as −10°C. Freeze injury symptoms were observed at both sites and some winter kill occurred in black oat during this time. Similar observations on cold tolerance of this species were made by Reeves et al. (1997) and Bauer and Reeves (1999).

Both growth stage and cover crop significantly affected biomass in 2000, but there were no significant interactions among cover crop and growth stage treatments (Table 1). All cover crops reached maximum biomass at the early milk growth stage. Wheat showed significantly lower biomass production, with a maximum biomass of 7.7 Mg ha^{-1}. Rye and black oat achieved higher maximum biomass (10.7 and 10.8 Mg ha^{-1}, respectively). These two crops also achieved a high amount of biomass by anthesis, which, as noted in the previous year's results, would allow for earlier termination and therefore an earlier planting date of a succeeding summer cash crop.

The differences observed in biomass production can be attributed, at least in part, to the selective use of the crop. Black oat was bred for use as a cover and forage crop to produce greater residue amounts, while most varieties of rye, and especially wheat, have been bred as grain crops. Thus wheat produces a greater percentage of the maximum biomass as grain, not as stems (residue).

Table 1. Cover crop biomass production (dry weight Mg ha^{-1}) by year, cover crop and growth stage for 1999 and 2000.

Cover crop	Growth stage	Biomass (Mg ha^{-1}) 1999[1]	2000
Black oat			
	Flag leaf	3.9	7.1
	Anthesis	8.6	10.0
	Early milk	–[2]	10.8
	Soft dough	7.8	–[2]
Rye			
	Flag leaf	4.9	6.9
	Anthesis	7.2	9.9
	Early milk	–[2]	10.7
	Soft dough	9.5	–[2]
Wheat			
	Flag leaf	4.9	3.6
	Anthesis	7.2	6.5
	Early milk	–[2]	7.7
	Soft dough	10.5	–[2]
$LSD_{(0.10)}$ growth stage within cover crop		1.33	1.40 (ns)
$LSD_{(0.10)}$ growth stage		0.77	0.81
$LSD_{(0.10)}$ cover crop		0.70	0.68

[1] Data averaged over two sites.
[2] Data not taken at this growth stage.

Cover-crop C:N ratio

The C:N ratio of cover crops serves as an important indicator of the decomposition rate of residue and resulting amount of soil coverage (Ranells and Wagger, 1996; Reeves,1994; Wagger, 1989). The relatively high C:N ratio of cereal cover crops can also be a disadvantage due to increased nitrogen immobilization (Doran and Smith, 1991; Reeves, 1994; Somda et al., 1991). In 1999, there were significant site × cover crop × growth stage and site × cover crop interactions for C:N ratios of cover crops (Table 2). Thus, sites will be discussed separately. The significance of site may be attributed to differences in available soil N and prior uses of the plot areas at each site. Wagger and Mengel (1988) found that the N content of small-grain cereals depends on available soil N.

On the Compass loamy sand, a significant cover crop × growth stage interaction was observed. Black oat showed no significant increase in C:N ratio from anthesis to the soft dough growth stage (38:1 and 39:1, respectively). Wheat had no significant changes in ratio from flag leaf to anthesis (32:1 and 31:1, respectively). Rye followed the expected trend of increasing ratio with increasing maturity (flag leaf 24:1, anthesis 34:1, and soft dough 64:1). The high C:N ratios of small-grain cover crops can be a disadvantage when N is immobilized (Doran and Smith, 1991; Reeves, 1994; Somda et al., 1991). By delaying kill time, there is an increase in potential for N immobilization. This was especially important with rye, which had very high C:N ratios at the last growth stage.

A significant cover crop × growth stage interaction for C:N ratios was also observed on the Cahaba sandy loam in 1999. The C:N ratios of all cover crops increased with maturity. Black oat and wheat increased C:N ratios from

Table 2. Cover crop C:N ratio by year, site (soil type), cover crop, and growth stage for 1999 and 2000.

Year Site (soil type)		1999 Cahaba	1999 Compass	2000 Compass
Cover crop	**Growth stage**		**C:N ratio**	
Black oat				
	Flag leaf	21	23	27
	Anthesis	34	38	37
	Early milk	–[1]	–[1]	37
	Soft dough	45	39	–[1]
Rye				
	Flag leaf	21	25	26
	Anthesis	25	35	44
	Early milk			56
	Soft dough	48	64	–[1]
Wheat				
	Flag leaf	23	32	23
	Anthesis	32	31	31
	Early milk	–[1]	–[1]	36
	Soft dough	37	45	–[1]
$LSD_{(0.10)}$ growth stage within cover crop		7.1	6.2	4.9
$LSD_{(0.10)}$ cover crop		4.1	6.0	3.9

[1] Data not taken at this growth stage.

flag leaf through soft dough, while rye increased only from anthesis (25:1) to soft dough (48:1).

In 2000 on the Compass loamy sand, a cover crop × growth stage interaction was observed. Rye and wheat C:N ratios increased linearly with growth stage (Table 2). The C:N ratio did not significantly increase after anthesis in black oat (37:1 at anthesis and early milk), similar to the previous year at this site. The ratios measured were relatively consistent with those of other studies (Bauer and Reeves, 1999; Reeves, 1994; Wagger, 1989).

The ratios varied greatly across site-years, cover crops and growth stages, making it difficult to interpret data for consistent trends. However, rye was identified as having the greatest C:N ratio at the most mature growth stages (Feekes' 10.54 and 11.2). Black oat and wheat were similar in C:N ratio at these stages and were consistently lower than rye. Bauer and Reeves (1999) saw similar results in their study, where rye averaged higher ratios than those of oat, wheat and black oat. An increase in C:N ratio of rye was also shown by Wagger (1989) when two termination dates were compared.

Percent kill

A linear relationship between plant moisture content and visual percent kill ratings was observed in 1999 ($r^2 = 0.56$, $P \leqslant 0.01$) and 2000 ($r^2 = 0.52$, $P \leqslant 0.01$), validating use of visual ratings. Measurements taken at 28 days are presented for brevity and consistency in correlation to plant moisture content. However, it should be noted that after 14 days there were no significant increases in percent kill at any site-year.

A significant cover crop × growth stage × kill method interaction was observed (Fig. 2). At flag leaf, the label rate of paraquat and the one-half label rate paraquat + roller-crimper combination had a significantly lower kill mean, especially on black oat (26 and 28%, respectively), than glyphosate treatments. The roller-crimper alone was not able to effectively kill plants at flag leaf (13%, 16%, and 26% termination for black oat, rye and wheat, respectively). At flag leaf, cover-crop plant height was relatively low and plant stems were still elongating. At anthesis, the label rate of paraquat and the one-half label rate paraquat + roller-crimper combination were as effective (mean 93% kill) as the glyphosate treatments. Roller-crimper efficacy increased at anthesis to an average of 81%, but this is still significantly less effective than chemical and combination treatments at this growth stage. At anthesis, the roller-crimper was most effective on black oat (88%) compared to wheat (81%) and rye (74%). By soft dough, all kill methods were equally effective due to accelerating plant maturity and senescence (95% mean kill across all cover crops and kill methods).

At anthesis and soft dough, a combination of the roller-crimper and a half rate of either herbicide performed just as well as the herbicides alone at the label rate. The 1999 data indicated that the critical period lay between the anthesis and soft dough growth stages. During 2000, the last growth stage tested was changed to refine the most effective time to use the roller-crimper method.

In 2000, a significant cover crop × growth stage × kill method interaction was observed, similar to the previous year (Fig. 3). At the flag leaf growth stage, the effectiveness of the roller-crimper was low, with a kill mean of only 16% across all cover crops. Roller-crimper efficacy increased at anthesis to 85%. However, waiting until early milk (usually only 7–10 days after anthesis) resulted in 93% effectiveness by the roller-crimper; the average effectiveness of all other treatments was 95% when averaged over cover crops.

The full rate of glyphosate had equal kill effectiveness on all cover crops at all growth stages, averaging 95%. With the exception of wheat at the flag leaf growth stage, where kill was 49%, glyphosate at one-half label rate in combination with the roller-crimper had equal kill at all growth stages across all covers (averaging 95%). Paraquat at the full label rate was more effective at the flag leaf stage on rye (94%) compared to wheat (81%) and black oat (80%). Similar results were obtained with the one-half label rate paraquat + roller-crimper combination, where it was more effective on rye (88%), than on black oat (61%) and wheat (51%).

There were a few distinguishable similarities across all site-years. In both years it was shown that the flag leaf stage was too early to get an effective kill by using the roller-crimper alone. By anthesis, the one-half label rate + roller-crimper combinations were as effective as the label rate of either chemical used alone. By waiting the additional 7–10

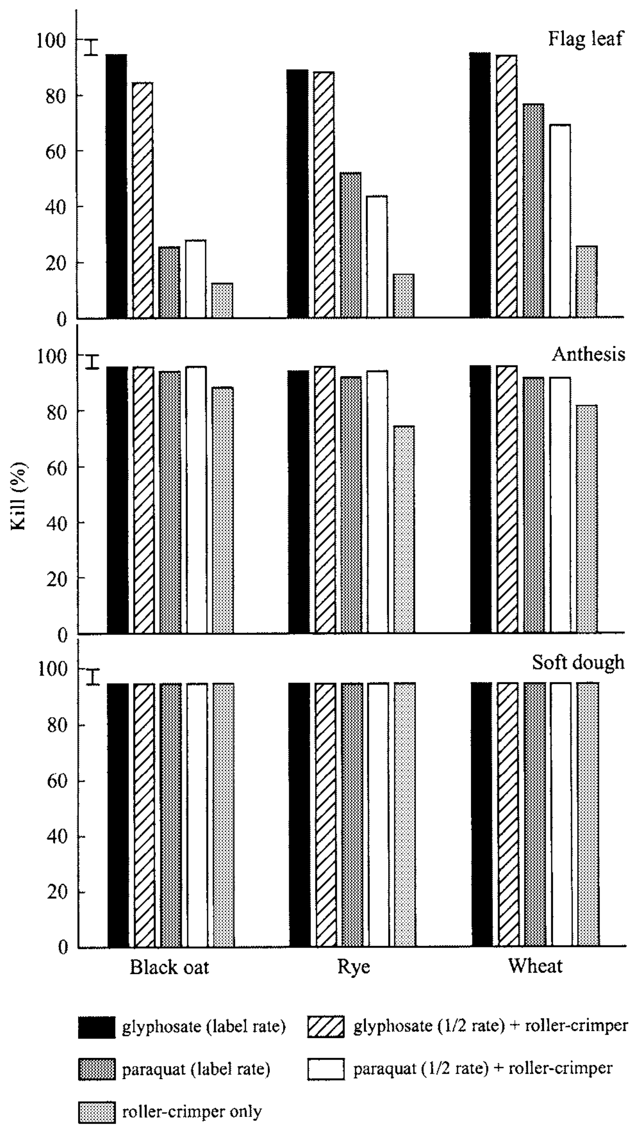

Figure 2. Percent kill 28 days after treatment by cover crop, growth stage and kill method during 1999. (Vertical bars denote $LSD_{(0.10)}$ kill method within growth stage by cover crop = 6.2%.)

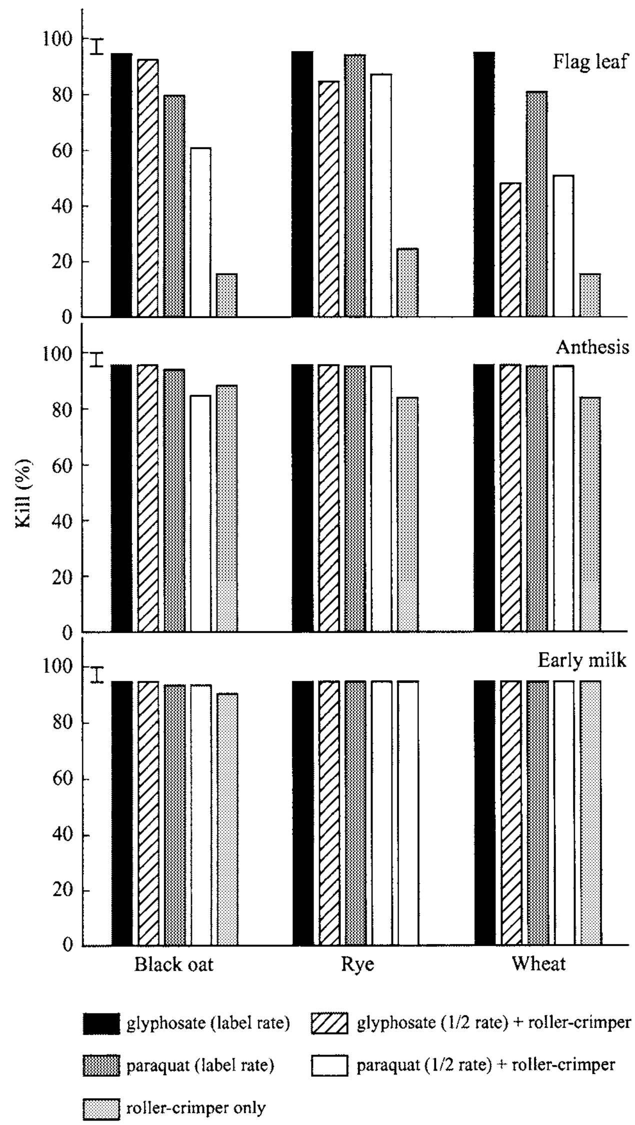

Figure 3. Percent kill 28 days after treatment by cover crop, growth stage and kill method during 2000. (Vertical bars denote $LSD_{(0.10)}$ kill method within growth stage by cover crop = 7.1%.)

days after anthesis to early milk (or later to the soft dough growth stage), we found complete kill of all three cover crop species with use of the roller-crimper alone.

Soil water conservation

There were no significant site interactions in 1999 for soil water, despite small differences in soil texture, so results are averaged across both sites (Fig. 4). For reference, volumetric water content at field capacity is typically about $100\,g\,kg^{-1}$ (10%) and $123\,g\,kg^{-1}$ (12.3%) and permanent wilting point (PWP) is $50\,g\,kg^{-1}$ (5%) and $58\,g\,kg^{-1}$ (5.8%) for a sandy loam (Cahaba soil) and loamy sand (Compass soil), respectively (Miller and Donahue, 1990).

A significant cover crop × growth stage × kill method interaction was observed during 1999 (Fig. 4). Soil water content measurements at the flag leaf growth stage were directly related to efficacy of kill method. Ineffective kill methods resulted in depletion of soil water by the still-growing cover crops. A significant linear relationship was observed between percent kill (visual ratings) and soil water content ($r^2 = 0.37$, $P \leq 0.01$); as percent kill increased, soil water increased. Glyphosate treatments, which resulted in the best kill, had the highest soil water content for all cover crops at flag leaf ($111\,g\,kg^{-1}$). However, in wheat, soil water following paraquat treatments ($95\,g\,kg^{-1}$) was not significantly different than soil water when wheat was treated with glyphosate ($114\,g\,kg^{-1}$). Paraquat treatments were especially ineffective at terminat-

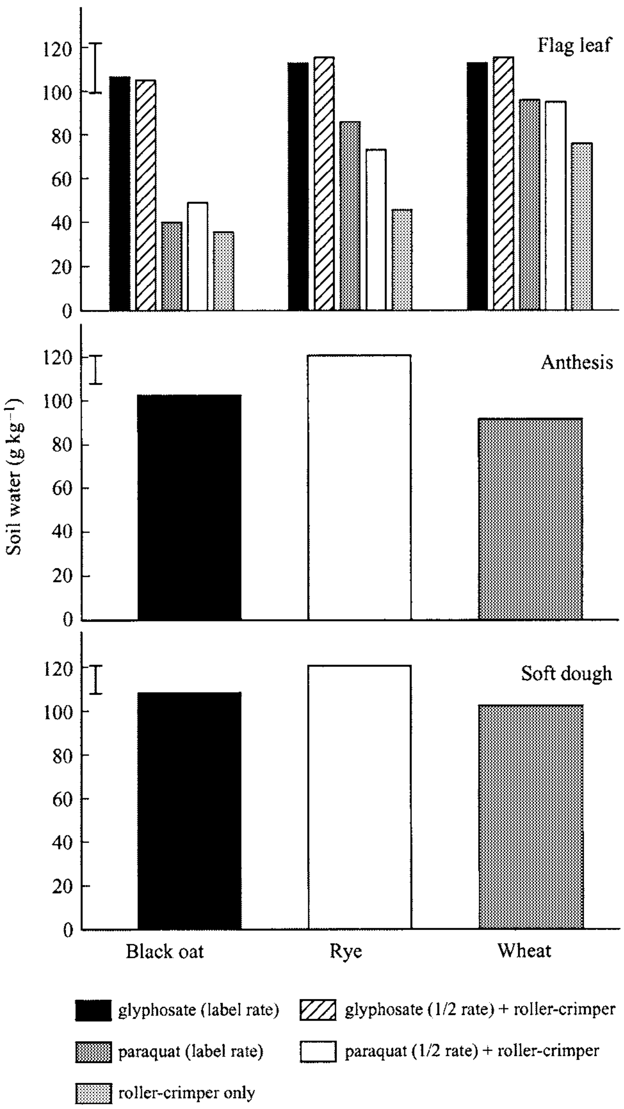

Figure 4. Soil water 28 days after treatment by cover crop, growth stage and kill method during 1999. (Vertical bars denote $LSD_{(0.10)}$ kill method within growth stage by cover crop = 20.3 g kg^{-1} and $LSD_{(0.10)}$ cover crop within growth stage = 15.3 g kg^{-1}.)

ing black oat, resulting in soil water depletion significant enough to likely affect emergence of a cash crop (45 g kg^{-1}). At flag leaf, the roller-crimper only treatment was the least effective kill method and therefore resulted in the lowest soil water content in all cover crops (50 g kg^{-1}). Considering the average PWP of the soils at both sites (54 g kg^{-1}), soil at this water content would not be adequately moist enough to plant a cash crop.

In 1999, there were no significant differences in soil water 28 days after treatment for any cover crop as a result of kill method at the anthesis or soft dough growth stages (average over all treatments was 103 g kg^{-1}). The lack of significant difference in soil water between kill methods was the result of high kill efficacy at these two growth stages. Although the roller-crimper efficacy was significantly lower than all other methods for all cover crops at anthesis, the soil coverage provided by the residue mat created by the roller-crimper resulted in soil water conservation and similar soil water contents (94 g kg^{-1}).

When cover crops were killed at anthesis and soft dough, a significant but weak linear relationship was observed between cover-crop growth (biomass production) and soil moisture content (r^2 = 0.11; $P \leqslant 0.01$). When killed at anthesis, rye resulted in greater soil water (118 g kg^{-1}) than either black oat or wheat (100 and 90 g kg^{-1}, respectively), but rye biomass (7.2 Mg ha^{-1}) was less than, or equal to, that of black oat (8.6 Mg ha^{-1}) and wheat (7.2 Mg ha^{-1}) at this growth stage. When killed at soft dough, soil water within wheat (100 g kg^{-1}) was less than under rye or black oat (120 and 110 g kg^{-1}, respectively). Wheat reached maximum biomass at the soft dough stage mainly due to its high harvest index. This resulted in less straw to provide soil coverage and may account for the lower soil water. However, these soil water contents were all near field capacity and would be ideal for planting a cash crop in May. Early May is the normal planting window for cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.), the most popular cash crops in the region.

Severe water deficits existed during spring 2000, therefore soil moisture data taken after the flag leaf stage are not presented. There was no measurable rainfall between 24 April and 22 May when soil water measurements were taken for all plots, excluding those terminated at the flag leaf growth stage. The rainfall in April–May of 2000 (92 mm, 45 mm of which fell after 22 May when all sampling was complete) was severely deficient, compared to 1999 (147 mm) and the normal rainfall for these 2 months (232 mm). All measurements taken during anthesis and early milk growth stages showed values not suitable for planting a cash crop (all values were below the PWP of 58 g kg^{-1} for a Compass loamy sand). Measurements taken from plots terminated at the flag leaf stage reflected the results of the previous season, with the amount of soil water being related to kill efficacy. The glyphosate and paraquat alone treatments and the one-half label rate glyphosate + roller-crimper combination, which resulted in the best kill means, had the highest soil water content for all cover crops at flag leaf (101, 82 and 84 g kg^{-1}, respectively). The roller-crimper alone was the least effective kill method at the flag leaf growth stage and consequently resulted in a soil water content (averaged over all cover crops) of 47 g kg^{-1}, which is below the PWP of 58 g kg^{-1}.

It is suggested, due to the results of the first season of this study, that kill should take place after anthesis, as this stage exhibited good kill efficacy, reduced water uptake by plants prior to cash-crop planting, and provided sufficient biomass to provide soil coverage. The use of a roller-crimper can also be recommended when killing after anthesis, due to water conservation benefits that occur due to increased soil coverage provided by the residue mat created by the roller-crimper. Blevins et al. (1971) and Munawar et al. (1990)

showed the benefit of cover-crop residue to conserve soil moisture, by decreasing evaporation and runoff, as well as increasing the ability of soil to store moisture.

Weed biomass

The two dominant weed species observed at both sites and both growing seasons were cutleaf evening primrose (*Oenothera laciniata* Hill) and wild mustard [*Brassica kaber* (D.C.) L. Wheeler]. In 1999, weed biomass was highly variable (c.v. 292%), with values so low (averaging 0.05 Mg ha^{-1}) as to have little practical significance. During 2000, the amount of weed dry matter produced was 0.02 Mg ha^{-1}, averaged over all factors, which holds little practical significance, and the results, similar to the previous season, were highly variable (c.v. 186%).

Although there were significant treatment effects, the high variability makes them difficult to understand. In general, the overall effect on weed biomass was related to amount of residue present, which, in turn, was related to growth stage and delayed kill of the cover crop. By delaying termination, residue increased in biomass, increasing the amount of soil coverage and weed shading. This delay also resulted in an increased C:N ratio of the residue, slowing the rate of decomposition and providing longer-lasting soil coverage for weed suppression.

Conclusions

This study shows that it is possible using a roller-crimper to effectively terminate cereal cover crops with reduced herbicide inputs. When termination occurs at early milk (Feekes' 10.54) or later, the use of herbicides may be eliminated. At this stage, all kill methods were equally effective (94% across all cover crops). There were no significant differences between cover crops in terms of percent kill when the roller-crimper was used; the main determining factor was growth stage. As a mechanical alternative to herbicides for killing cover crops, energy requirements for operation of a roller-crimper are estimated to be one-tenth that of a rotary mower. Energy coefficients for paraquat (493 MJ kg^{-1}; Ess et al., 1994) and glyphosate (454 MJ kg^{-1}; McLaughlin et al., 2000) are similar. Using the roller-crimper at anthesis in combination with one-half label rate of either of these herbicides would, of course, reduce the energy required to kill a small-grain cover crop. However, we emphasize that the roller-crimper is designed for use in no-tillage systems. Although no-tillage systems may require more energy for herbicides, less is required for machinery, fuel and labor, and total system energy requirement is less with no-tillage than for conventional tillage (Clements et al., 1995; Ess et al., 1994). Based on operating costs for a similar type implement (cultipacker), the use of a roller-crimper costs \$3.73 ha^{-1}, which is significantly less than herbicide treatments alone (\$29.64 ha^{-1} for glyphosate and \$25.16 ha^{-1} for paraquat at current prices and label rates) when variable costs are compared (Prevatt et al., 2001). Risk-averse farmers could use one-half label rate + roller-crimper combinations after anthesis, while organic farmers may benefit by delaying kill until early milk or later and eliminating all chemicals. Producers should note, however, that use of a herbicide in a manner inconsistent with the label is technically a federal violation. Therefore it will be necessary for herbicide manufacturers to adjust labels to address use with roller-crimpers. We have observed that no-till planting in the same direction as the cover crop was rolled facilitates seed–soil contact and reduces residue hair-pinning. Use of the roller-crimper provides additional benefits while killing cover crops, as it lays residue flat on the soil surface, providing maximum soil coverage, thereby preventing erosion, decreasing soil water evaporation and providing weed control.

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