Summary  Two trials were set up in Western Australia to investigate the effect of windrow management on the control of annual ryegrass in the following season. Windrow burial was compared to burning and diuron application and the effects of these on annual ryegrass emergence and cereal yield was measured.

Windrow burial by a mouldboard plough was the most successful control strategy reducing annual ryegrass densities by over 99% resulting in a two-fold increase in cereal yields. Windrow burning had mixed success, reducing annual ryegrass numbers at one site but not the other, emphasising the importance of sufficient heat for a good seed kill. The success of diuron application was also mixed and was likely to be dependent on the amount of harvest residue in the windrow. Large numbers of annual ryegrass emerged in the areas between the windrows making post-emergent control difficult due to herbicide resistance.

The decision to windrow and the subsequent windrow treatment for annual ryegrass control depends on the season at harvest and the conditions at the site leading up to sowing.

Keywords  Annual ryegrass, mouldboard plough, burning, herbicides, windrow.

INTRODUCTION

In Western Australia, annual ryegrass (Lolium rigidum Gaud.) is a major cropping weed due to widespread herbicide resistance and the ability to produce thousands of seeds. Successful cropping programs are heavily reliant on integrated weed management techniques especially where annual ryegrass is resistant to post-emergent herbicides.

As annual ryegrass seed is held tightly and not immediately shed at maturity, a large proportion of the total seed (60–80%) can be caught at harvest (Gill 1996). The seed and harvest residue can be channelled into windrows then treated to kill or remove the viable seeds. Windrowing and subsequent weed seed management can be relatively cheap and environmentally sustainable due to the treatment of only 10–15% of the paddock.

This project, funded by the Department of Agriculture Western Australia, arose from previous work with soil inversion for annual ryegrass control across whole paddock situations (Douglas and Peltzer 2004).

As the soils in Western Australia are sometimes sandy and subject to wind erosion under adverse conditions as well as an opposition to ploughing after years of conservation tillage, it was decided to investigate the inversion of the windrow only. Included in the study were the effects of burning or application of a residual herbicide to the windrow.

Burning for annual ryegrass control is traditionally done on a whole-paddock basis on standing stubble. As its effectiveness depends on the temperature and duration of the fire, which is determined by the available fuel, windrow burning is a more effective way to kill annual ryegrass seed compared to standing stubble (Chitty and Walsh 2003). The paddock is also less prone to wind erosion after windrow burning.

The application of residual herbicides onto hot dry soils and stubble allow for persistence of some residual herbicides. Diuron and oryzalin reduced annual ryegrass numbers when sprayed onto stubble over summer and early autumn (Walsh et al. 2005). Diuron has also previously reduced the numbers of annual ryegrass in windrows (Michael Walsh pers. comm.).

This paper reports on the effect of windrow inversion, burning and the application of diuron on the reduction in viable annual ryegrass seed in two locations in Western Australia.

MATERIALS AND METHODS

Different windrow management techniques were investigated for their effectiveness to control annual ryegrass in the south-west land division of Western Australia. Two sites (Mount Barker, 34.6°S, 117.6°E, gravel loam and Katanning 33.7°S, 117.5°E, sand over loam) with high populations of annual ryegrass were selected prior to harvest in 2003. A heavy crop of oats (>5 t grain ha⁻¹) was harvested at Mount Barker in 9.5 m strips with the straw either spread or left in windrows and ungrazed over summer. Similarly, a wheat crop (2 t grain ha⁻¹) at Katanning was harvested in 10 m strips, spread or left in windrows and ungrazed over summer.

In 2004, six treatments were implemented at both sites either in autumn or directly prior to seeding:
1) Harvest residue windrowed (Control 1).
2) Harvest residue spread (Control 2).
3) Harvest residue windrowed, windrow burnt in
autumn then buried by a mouldboard plough (with skimmers) prior to seeding.
4) Harvest residue spread then the entire plot buried by a mouldboard plough (with skimmers) prior to seeding.
5) Harvest residue windrowed then windrow burnt in autumn prior to seeding.
6) Harvest residue windrowed then windrow sprayed with diuron (1.5 kg a.i. ha\(^{-1}\)) in autumn prior to seeding.

Measurements taken from both trial sites included crop and annual ryegrass densities, dry weights at anthesis and grain yield and grain protein.

The Mount Barker site was pre-treated with a double knockdown (glyphosate followed two days later by paraquat/diquat) then sown with knifepoints to wheat (cv. Wyalkatchem at 120 kg ha\(^{-1}\)) with 100 kg ha\(^{-1}\) monoammonium phosphate. Post seeding treatments included a mixture of metosulam and triasulfuron for broadleaf control.

The site at Katanning was also pre-treated with a double knockdown then sown with 125 kg ha\(^{-1}\) of barley cv. Gairdner with 100 kg ha\(^{-1}\) of basal fertiliser (15.5 kg N ha\(^{-1}\)). Metsulfuron was applied post-emergence for broad-leaf control. Nitrogen was topdressed at 27 kg ha\(^{-1}\).

**RESULTS**

Accumulating the harvest residue into windrows concentrated the annual ryegrass seed (Table 1, P <0.05). At Katanning, the number of emerged annual ryegrass seedlings was more than six times greater within the windrow compared to the bulk area between when no weed control was implemented (Control 1). When the harvest residue was spread across the whole plot (Control 2), over 2000 seedlings m\(^{-2}\) emerged. Similarly, there was an accumulation in the number of seeds in the windrows at Mount Barker, however the percentage was less.

There were over 300 seedlings m\(^{-2}\) in the bulk area between windrows in all treatments that were windrowed at both sites.

Burying the windrow by mouldboard plough (after burning) was the most successful windrow treatment for annual ryegrass management. Less than 20 annual

<table>
<thead>
<tr>
<th>Harvest residue</th>
<th>Katanning Bulk area</th>
<th>Katanning Windrow</th>
<th>Mount Barker Bulk area</th>
<th>Mount Barker Windrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>windrowed</td>
<td>562</td>
<td>3842</td>
<td>487</td>
<td>1638</td>
</tr>
<tr>
<td>(Control 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spread</td>
<td>272</td>
<td>633</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Control 2)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>LSD (P = 0.05)</td>
<td>1209</td>
<td>552</td>
<td></td>
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</table>

**Figure 1.** The effect of three windrow treatments on the seedling emergence of annual ryegrass the following year at Mount Barker and Katanning, Western Australia (mean of three replicates). (LSD (P = 0.05), Katanning = 2114, Mount Barker = 894).

**Figure 2.** The effect of three windrow treatments on the cereal yield within the windrow at Mount Barker and Katanning, Western Australia (mean of three replicates). (LSD (P = 0.05), Katanning = 0.44, Mount Barker = 0.96).
ryegrass plants m^{-2} emerged in the buried windrows at both sites compared to over 1600 and 3800 in the untreated controls at Mount Barker and Katanning respectively (Figure 1, P <0.05). Similar low numbers of annual ryegrass were counted when the whole plot area was treated with a mouldboard plough (data not shown). Where the windrow was buried, a burn was required prior to ploughing to reduce the amount of residue. Some commercial skimmers can bury very heavy stubble but only lighter skimmers were available for these experiments.

The treatment of the windrows by burning or diuron application to control annual ryegrass had mixed success (Figure 1). Windrow burning successfully reduced annual ryegrass numbers to approximately 100 plants m^{-2} at Mount Barker (P <0.05). At Katanning however, there were visually higher annual ryegrass numbers in the burnt windrow compared to the control although this was not statistically significant.

The application of diuron to the windrows in autumn did not reduce the numbers of annual ryegrass seedlings in the windrows at Mount Barker. At Katanning, they were reduced by over 50% (P <0.10).

The annual ryegrass seedling numbers were reflected in the subsequent yields (Figure 2). The yields within the windrows at both sites were over double those within the control after mouldboard ploughing. Burning the windrow at Mount Barker resulted in over twice the wheat yield but had no effect at Katanning. Cereal yield increased after diuron application at Katanning but not at Mount Barker.

DISCUSSION
Windrowing can collect a large amount of weed seed with the harvest residue. In this investigation, over 75% of annual ryegrass seed was captured, accumulated with the harvest residue and concentrated in windrows, ready for the differing control treatments.

Seed burial by a mouldboard plough was the most effective annual ryegrass control treatment, reducing seedling numbers to less than 0.5% of the control. The single mouldboard operation buried the seed at a depth greater than 15 cm, from where seedlings were unable to emerge (Gramshaw and Stern 1977 and Douglas and Peltzer 2004). This resulted in a doubling of the yield at both sites predominantly due to the reduction in crop-weed competition. Some of the increased yield could also be due to increased soil nitrogen mineralisation due to soil disturbance (Douglas and Peltzer 2004) as the crops in some of these plots looked visually greener in spring. It is unlikely that windrow burial by a mouldboard plough would be feasible in practice due to the deep furrows left by the first mouldboard pass i.e. leaving numerous trenches across the paddock.

However, a recent innovation in the Spot Plough, offers complete inversion tillage within a single specific row (Shoji 2003). The inverted soil slice can be placed on its own furrow. This has yet to be tested in Western Australian conditions.

Windrow burning was an effective seed control method at Mount Barker, reducing the emergent seedlings by over 90%. The burning operation took place in March and there was a large amount of residue produced from the high yielding oat crop the previous year. At Katanning however, burning failed to reduce annual ryegrass numbers. The windrows were burnt late in autumn when the residue was damp so it is likely that the burn was not hot enough to kill the annual ryegrass seed. A laboratory study in Western Australia by Chitty and Walsh (2003) showed that burning at temperatures of 400°C for 20 seconds destroyed all annual ryegrass seeds. At cooler temperatures, for example, 250°C, seeds need to be exposed for at least 60 seconds to get the same result. Although not significant, the burnt windrows at Katanning had visually higher seedling levels than those of the control. It is likely that the mulching effect of the unburnt windrow either killed some of the seed or did not allow them to emerge.

Diuron application was the least successful seed control method, marginally reducing seedling numbers with slightly higher barley yields at Katanning. There was no effect at Mount Barker. Previous studies where 2.5 kg ha^{-1} of diuron was broadcast directly onto stubble in autumn resulted in a 93% reduction in annual ryegrass seedlings (Walsh et al. 2005). It is likely that high residue levels, especially at Mount Barker, did not allow the herbicide to travel deep enough through the windrow to kill the seeds underneath.

The choice to windrow for control of annual ryegrass depends on the lateness of the season and how much of the weed is lying down with the crop. Observations have indicated that less annual ryegrass seed is caught as the harvest is delayed, due to shedding of seed from the heads. This is particularly pertinent in the southern areas for Western Australia where harvest is often delayed by rain. The trial at Mount Barker was harvested approximately one month after Katanning, in mid-January, 2005, and proportionally less seed was accumulated in the windrows. Should these plants be herbicide resistant, there will be very few options for post-emergent control. These plants can still reduce yields and produce thousands of viable seed for following season. An earlier study showed that 500 annual ryegrass plants m^{-2} at Katanning produced over 10,000 seedlings m^{-2} over the next three years (Peltzer and Matson 2002). In the northern parts of the Western Australian wheatbelt, harvests are less...
likely to be delayed and seed-catching is widely used as a reliable method of seed removal (Peter Newman, pers. comm.).

It is important to choose the annual ryegrass management strategy carefully, pertinent to the conditions and season of the site. Windrowing may not be an option in seasons with a late harvest making whole paddock treatments more viable. Subsequent windrow treatments may also depend on the soil type, the amount and type of harvest residue and other conditions relevant to the site.

ACKNOWLEDGMENTS
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REFERENCES


