Integrated weed management in dry-seeded rice using stale seedbeds and post sowing herbicides

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**ABSTRACT**

Dry-seeded rice (DSR) grown with alternate wetting and drying water management (AWD) has recently been introduced in northwest India as an alternative to conventional puddled hand-transplanted rice which is labour, water and energy intensive. The aerobic seedbed of DSR can be extremely susceptible to invasion by diverse weed flora, and if weeds are not controlled effectively, yield losses can be very high. This study was undertaken to investigate the impacts of stale seedbed techniques on the soil weed seedbank and weed infestation in DSR, and to determine the influence of integration of the stale seedbed methods with post sowing herbicides on weed control and rice grain yield. The study, conducted in 2014 and 2015, comprised three seedbed treatments in main plots: without stale seedbed-conventional method, stale seedbed with glyphosate 1 kg ha⁻¹and stale seedbed with shallow (5 cm) tillage, and four post sowing herbicide treatments in sub plots: unsprayed check, pendimethalin 0.75 kg ha⁻¹ (pre-emergence), bispyribac-sodium 0.025 kg ha⁻¹ (post-emergence) and pendimethalin followed by bispyribac-sodium. The two stale seedbed treatments included one additional irrigation prior to sowing which increased weed seedling emergence prior to sowing by 1.9–2.2-fold; weeds in the stale seedbed treatments were then killed with the application of glyphosate or shallow tillage. At sowing, both stale seedbed treatments significantly decreased the viable seedbank of *Echinochloa colona* and *Dactyloctenium aegyptium* to 25–30% of that without a stale seedbed. After rice harvest, both stale seedbed treatments had a significantly lower seedbank than without a stale seedbed, by 13–33%; the stale seedbed with tillage had significantly lower seedbank at harvest than the stale seedbed with glyphosate in the second year. The sequential application of pendimethalin and bispyribac resulted in a significantly lower seedbank of both these grass weed species at harvest. At 20 DAS, both stale seedbed methods had 22–51% lower density of *Cyperus rotundus* and 42–67% less grass weeds than rice sown without a stale seedbed. There was more than a 2-fold increase in *C. rotundus* density from 2014 to 2015 without a stale seedbed and with the stale seedbed with glyphosate, and a 1.6-fold increase in the stale seedbed with tillage. In the absence of post sowing herbicides, the stale seedbed with tillage increased grain yield from 0.7–1.0 t ha⁻¹ to 2.1–2.5 t ha⁻¹, while the stale seedbed with glyphosate only increased grain yield in 2015. The combination of the stale seedbed with tillage, pendimethalin and bispyribac had the highest rice grain yield (7.3 t ha⁻¹) and the highest economic returns ($1310 ha⁻¹); the returns in this treatment were $260 ha⁻¹ higher than using the same herbicides used without a stale seedbed. The results indicate that integrated use of a stale seedbed with shallow tillage followed by the sequential application of post sowing herbicides has potential to control the complex weed flora in dry-seeded rice. The reasons for greater consistency in weed control with the stale seedbed with tillage than glyphosate are unclear and need further investigation in dry seeded rice, as do the long term effects of use of stale seedbeds.

1. Introduction

Rice, a staple food of India grown on 43.4 million ha (Anon., 2016), has been traditionally established in puddled soil by hand-transplanting, and this remains the most common practice in northwest India including Punjab and Haryana. Puddling (wet tillage) benefits rice by reducing water percolation losses, killing weeds, facilitating transplanting of rice seedlings, and creating anaerobic conditions which enhance nutrient availability (Sanchez, 1973). Repeated puddling, however, destroys the soil aggregates resulting in a massively structured topsoil and a shallow (typically within 15–25 cm soil depth) hardpan of low permeability (Kukal and Aggarwal, 2003a,b). The...
deterioration in soil physical properties can negatively affect the growth of upland crops grown in a rotation with rice (Aggarwal et al., 1995; Gajri et al., 1999; Gathala et al., 2011). In a recent survey in Punjab (Bhullar et al., 2018), farmer respondents (n = 211) reported 4.8% (0.3 t ha\(^{-1}\)) higher grain yield of wheat after non-puddled drill-sown dry-seeded rice (DSR) than after puddled hand-transplanted rice (PTR) (p < 0.1).

In PTR, wet tillage and continuous flooding for the first 15d after transplanting requires a large amount of irrigation water (e.g. 425–810 mm) (Sudhir-Yadav et al., 2011) and the puddling process requires large input of energy (2016–2390 MJ ha\(^{-1}\)) (Verma and Dewangan, 2006). Furthermore, hand-transporting into the puddled soil requires large labour input (300–350 man-ha\(^{-1}\)) (Bhatt et al., 2016). This was not a major impediment until about 10 years ago when labour scarcity and the associated rise in labour costs decreased rice profitability and became a major challenge for rice growers in Punjab and Haryana. Kamboj et al. (2013) identified labour scarcity as the biggest hurdle for sustainable agriculture in this region. The declining water table, increasing costs of labour, diesel and electricity and increased rainfall variability due to climate change have emerged as serious issues for the traditional hand-transported rice production system (Gill et al., 2013). Therefore, many researchers and policy makers have highlighted the need to develop alternative rice production systems for this region.

Recent research conducted in north and eastern India underpinned the successful development of a drill-sown rice production system (Gill et al., 2013). Mechanised seeding of rice into dry or moist non-puddled soil is the fastest growing reduced till technology in the Indian Punjab; the area under dry-seeded rice (DSR) increased to 115,000 ha in 2014 from < 1000 ha in 2010 (Anon., 2014). The major drivers of adoption are the lower cost of rice establishment, ability to plant on time, lower amount of irrigation water needed to establish DSR, and the rising interest in conservation agriculture (Mahajan et al., 2013; Kumar and Ladha, 2011; Bhullar et al., 2018). When all components of the DSR system are implemented effectively, grain yield can be similar to that of PTR (Gill et al., 2013; Sudhir-Yadav et al., 2011; Bhullar et al., 2018). Furthermore, the combination of dry-seeding and alternate wetting and drying water management (AWD) reduces irrigation input and increases irrigation water productivity in comparison with PTR. As labour costs for crop establishment are much lower in DSR, net profitability can be greater than in PTR provided that weeds are adequately controlled (Bhullar et al., 2016b, 2018).

In PTR, rice seedlings are transplanted in the main field and therefore have a size advantage over weeds germinating in situ. Furthermore, continuous ponding of water in PTR suppresses the establishment of many weed species which are not adapted to flooded conditions. In contrast, DSR germinates and establishes at the same time as the weed seeds. The aerobic seedbed of DSR is also conducive to the germination and establishment of a more diverse weed flora than in PTR (Gill et al., 2013). Therefore, DSR can be extremely susceptible to invasion by weeds, if weeds are not controlled effectively, yield losses can be as high as 100% (Singh et al., 2014). Bhullar et al. (2016a) reported a strong negative correlation (\(r^2 = 0.95, p < 0.001\)) between weed biomass and DSR grain yield, which clearly highlights the poor competitive ability of DSR with weeds and the need to control weeds effectively during the whole growing season.

Since DSR fields are characterized by floristically diverse weed communities (Rao et al., 2007), a single herbicide cannot provide effective weed control. Mahajan et al. (2013) reported Echinochloa colona L., Leptochloa chinensis L., Digitaria sanguinalis L., Dactyloctenium aegyptium L., Eleusine indica L., Cyperus rotundus L. and Cyperus iria L. as major weeds in DSR in Punjab. A farmers’ survey conducted in 2014 indicated that during the early years of DSR adoption, the weed flora in DSR was very similar to that in PTR, but after 2 years the weed flora had shifted markedly towards grasses (Bhullar et al., 2018).

The stale seedbed technology has been used to manage weed infestations in many crops, including rice (Singh and Singh, 2012; Riemens et al., 2007; Dogan et al., 2009). This method of weed control involves wetting the soil to stimulate weeds to establish well before sowing of the crop. Weeds that establish prior to sowing can be killed with the use of non-selective herbicides or with tillage. If a stale seedbed can be used effectively, weed establishment in the forthcoming crop can be dramatically decreased. The reduced population of weeds that emerges after sowing can be controlled more effectively with herbicides. Weed seedlings emerging earlier are likely to be more competitive with the crop than seedlings emerging later in the crop (Cousens et al., 1987), and crop yield losses can be sensitive to small differences in the time of weed and crop emergence (Chikoye et al., 1995). The delay of weed emergence relative to the crop should be a basic principle guiding the development of weed management strategies (Liebmann and Gallandt, 1997; Chauhan and Johnson, 2010). Weed emergence may be delayed relative to the crop by management practices such as herbicide application or mechanical cultivation that kill a cohort of weeds or reduce their growth (Liebmann and Gallandt, 1997). When Echinochloa germination was delayed relative to that of rice, weed survival and rice yield loss were greatly decreased (Gibson et al., 2002). The integration of pre-and post-emergence herbicide application decreased rice yield loss by 23–27% compared with pre-emergence herbicide only (Bhullar, 2016a). Hence, the use of a single method of weed control is unlikely to provide effective weed control in DSR. While the potential for using herbicides to improve weed control when weed emergence is delayed under a stale seedbed appears to be substantial, this practice has not been investigated in DSR in northwest India. The effects of stale seedbeds using herbicides or tillage on the soil weed seedbank and weed dynamics is a knowledge gap for DSR in the region. Further, how weed flora and the rice crop respond to the interaction effects of stale seedbed methods and post-sowing herbicides has not been studied in DSR.

Therefore, the present study was conducted to test the following hypotheses: (1) the use of a stale seedbed and/or post sowing herbicide will deplete the soil weed seedbank, (2) the use of a stale seedbed with glyphosate or shallow tillage is equally effective in controlling weeds in DSR, and (3) the combination of a stale seedbed and post sowing herbicides will be more effective in controlling weeds and increasing yield in comparison with the use of post sowing herbicides alone.

## 2. Materials and methods

### 2.1. Experimental site

A field study was conducted under irrigated conditions in the kharif (summer) seasons of 2014 and 2015 at the research farm of the Punjab Agricultural University, Ludhiana, India. The soil (0–15 cm) was a sandy loam, pH (8.0), EC (0.13 dS m\(^{-1}\)), low in organic carbon (0.39%), extractable N (243 kg ha\(^{-1}\)), extractable P (8.8 kg ha\(^{-1}\)) and extractable K (337 kg ha\(^{-1}\)). The average bulk density of the soil was 1.55 g cm\(^{-3}\). The experimental field was under a pigeonpea-wheat system in 2011 and under a DSR-wheat system in 2012 and 2013.

The climate of the region is semi-arid sub-tropical, with a mean annual rainfall of 733 mm, most of which falls during the monsoon season (late June to September) (Fig. 1). The region has extremely hot and dry conditions with high evaporative demand at the optimum time for dry seeding (73 mm in second week of June). Once the rains start, temperature and pan evaporation decrease (Figs. 1 and 2), and humidity increases.

### 2.2. Experimental design

The experiment was conducted in a split-plot design with four replicates. Three seedbed treatments were compared in the main plots: (1) without a stale seedbed-conventional method (control), (2) stale seedbed with glyphosate @ 1 kg ha\(^{-1}\), and (3) stale seedbed with
that period (Figs. 1 and 2). Thereafter, irrigations were applied at 7 sowing to keep the seed zone moist under the hot dry conditions during the first two weeks after sowing to prevent iron deficiency. Irrigation was stopped 10 d before harvest. In the post sowing herbicide treatments, pendimethalin was sprayed onto the moist soil surface in the evening of the day of sowing and bispipyrac-sodium at 20 days after sowing (DAS). The herbicides were sprayed with a knap sack sprayer fitted with a flat fan nozzle using 500 L of water ha$^{-1}$ for pre- and post-emergence herbicide, respectively. The crops were manually harvested at the harvest-ripe stage in the last week of October 2014 and 2015. After manual threshing, the grain was separated from the straw by winnowing.

2.3. Data collection

2.3.1. Weed seedbank studies

Soil samples were collected from each plot at 0–5 cm soil depth with a core sampler (diameter 10.5 cm) before sowing and after harvesting each rice crop. The samples were washed with water and filtered using a 0.2 mm cloth to separate weed seeds from the soil. The weed seed samples were transferred to petri dishes (diameter 9 cm) lined with wet filter papers and placed in an incubator at 30 °C. The filters were kept moist and the number of germinated seeds was determined at weekly intervals until germination ceased (5 weeks).

2.3.2. Weed density and biomass

Weed density and biomass (above ground parts) were determined by harvesting a quadrat (40 cm × 40 cm) at two representative locations within each plot at 20 and 45 DAS. The aboveground weed samples were dried at 70 °C in an oven for 72 h and dry biomass was determined.

2.3.3. Rice straw, grain yield and panicle density

Rice grain and straw yield were determined by harvesting an area of 12.8 m$^2$ in the centre of each plot and grain yield was adjusted to 14% moisture content. Grain moisture content at the time of harvest was determined by moisture meter. The straw yield was expressed on sun drying basis.

2.3.4. Economic analysis

The prevailing market prices of inputs and outputs were used in calculating the economics of each treatment. All input and output costs were converted to US $ (15 = INR 65.38). The variable input costs (ha$^{-1}$) common to all treatment combinations included the costs of seed and seed treatment ($6.3$), fertilizers ($44$), pesticides ($12$), irrigations ($39$), human labour ($56.3$), tractor hours ($36$), harvesting ($45.8$), and interest ($7.2$). Additional costs as per treatment were the costs of one extra irrigation ($2.3$), shallow cultivation and land levelling (for the stale seedbed with tillage treatment) ($15$), Stomp 30 EC (pendimethalin) ($15$), Roundup 41 SL (glyphosate) ($15$), Nominee gold 10 SC (bispipyrac-sodium) ($23$), and spraying ($4$). The market price of the output (rice grain) was $222 t^{-1}$. The net economic returns were calculated by deducting the total cost of inputs from the gross economic returns (total sale price of rice grain).

2.4. Statistical analysis

All data were subjected to two-way analysis of variance (ANOVA) using a split-plot model (SAS 9.2, North Carolina) to evaluate the differences among treatments. Years and treatments were considered fixed effects, whereas blocks (nested within year) were considered random.
effects in the model. Weed density and biomass data were square-root transformed prior to analysis to normalise the distribution of residuals and back-transformed means are presented with mean separation based on transformed values. Where the ANOVA indicated that treatment effects were significant, means were separated at \( p \leq 0.05 \) with Tukey’s test. Year \times treatment interactions for weed seedbank, weed density and biomass, and rice grain yield were significant; therefore, data were analysed and presented separately for both years.

3. Results

3.1. Weather

The first and second cropping seasons experienced 474 mm and 558 mm rainfall from June to October, respectively, lower than the long-term average rainfall of 624 mm (average of 1991–2010). Each year, there was no rainfall between the time of the stalebed irrigation and the pre-sowing irrigation one week later. There was very little rainfall in June and October each year (Fig. 1). The 2014 season was drier from June through August than the long term average, while monthly rainfall in July-September in 2015 was similar to the long term values. Pan evaporation was very high in May and June each year (monthly means of 250–300 mm). Pan evaporation in June-September 2014 was higher than in 2015 and the long term average values, consistent with the lower rainfall in 2014. Monthly mean daily temperature in June-August 2014 was higher than in 2015 when values were similar to the long term average (Fig. 2).

3.2. Soil weed seedbank

In 2014, the initial viable weed seed numbers of \( E. \) colona were 728 m\(^{-2} \) and those of \( D. \) aegyptium were 651 m\(^{-2} \) in the 0–5 cm soil depth (Table 1). In 2015, the initial seedbank of both the weed species did not vary significantly among seedbed treatments, and was similar to the initial values in 2014. Both stale seedbed treatments significantly decreased the viable seedbank of \( E. \) colona at the time of sowing to around 30\% of that without a stale seedbed each year. The reduction in the viable seedbank of \( D. \) aegyptium was greater, to around 25\% of the seedbank without a stale seedbed. The use of both stale seedbed methods for two consecutive years decreased the seedbank at the time of sowing of both grass weeds by more (by 54\% in comparison to without a seedbed) than after one year (37\% reduction).

There were no weeds present in any seedbed treatment at the time of stale seedbed irrigation in both years. The stale seedbed treatments had 1.9–2.2-fold greater emergence of weed seedlings prior to sowing (and shortly prior to tillage or glyphosate application) than without a stale seedbed (Table 2). After rice harvest each year, without a stale seedbed, the weed seedbank of both weed species was higher than the initial seedbank (Table 1). However, both stale seedbed methods had a significantly lower seedbank after rice harvest than without a stale seedbed, by 13–33\%. As a result, the seedbank of both weed species in the stale seedbed treatments after rice harvest was generally similar to the initial seedbank each year.

The sequential application of pendimethalin and bispyribac resulted in a significantly lower seedbank of both weed species at harvest than all other treatments in both years (Table 1). Pendimethalin alone resulted in the highest seedbank of \( E. \) colona, and bispyribac alone resulted in the highest or equally highest seedbank of \( D. \) aegyptium. However, the post-herbicide treatments in 2014 did not significantly affect the initial seedbank nor the seedbank before rice sowing in 2015.

### Table 1

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Viable weed seeds m(^{-2} ) at 0–5 cm soil depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( Echinochloa ) colona</td>
</tr>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td>Sowing</td>
<td>Harvest</td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>358a&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Stale seedbed with glyphosate</td>
<td>233b</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>220b</td>
</tr>
<tr>
<td>Post sowing herbicide</td>
<td></td>
</tr>
<tr>
<td>Unsprayed check</td>
<td>–</td>
</tr>
<tr>
<td>Pendimethalin 0.75 kg ha(^{-1} )</td>
<td>–</td>
</tr>
<tr>
<td>Bispyribac-sodium 0.025 kg ha(^{-1} )</td>
<td>–</td>
</tr>
<tr>
<td>Pendimethalin 0.75 kg ha(^{-1} ) + bispyribac-sodium 0.025 kg ha(^{-1} )</td>
<td>–</td>
</tr>
<tr>
<td>Initial weed seed bank</td>
<td>728</td>
</tr>
</tbody>
</table>

<sup>1</sup> Means presented within each column with no common letter(s) are significantly different according to Tukey’s test \( p \leq 0.05 \); The interactions between seedbed treatments and post-sowing herbicide treatments were non-significant for weed seedbank; fb—followed by.

### Table 2

Effect of seedbed treatments on weed seedling emergence before tillage or glyphosate application in stale seedbed treatments.

<table>
<thead>
<tr>
<th>Seedbed</th>
<th>Weed emergence (seedlings m(^{-2} )*)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>525b</td>
</tr>
<tr>
<td>With stale seedbed</td>
<td>1148a</td>
</tr>
</tbody>
</table>

* Means presented within each column with no common letter(s) are significantly different according to Tukey’s test \( p \leq 0.05 \).

** Table 2**
When total weed density was considered, the glyphosate in 2014, but both methods were equally effective in reducing grass weed density than the stale seedbed with pendimethalin was used. The stale seedbed with tillage was more effective in comparison to no stale seedbed. However, the results were inconsistent in the case of pendimethalin (alone or followed by bispyribac) (Table 6). The stale seedbed with tillage decreased the density of all grass and broadleaf weeds in comparison to no stale seedbed. Among the post sowing herbicide treatments, the pendimethalin and bispyribac sequence had a significantly lower density of *E. indica*, *D. arvensis*, *E. indica* and *D. arvensis* than the other weed control treatments (Tables 5–7). Bispyribac had the highest efficacy against sedges, however, in the case of *C. rotundus* it only provided growth suppression and not complete kill; it was weak against *D. aegyptium* and *E. indica*. For *D. aegyptium*, integration of the stale seedbed with tillage and sequential application of pendimethalin and bispyribac had the lowest weed density; with bispyribac alone, *D. aegyptium* density was significantly higher than or similar to that in the unsprayed check for all seedbed treatments except for the stale seedbed with tillage in 2014 (Table 7).

3.4. Weed biomass

There was a significant interaction between seedbed treatment and post sowing herbicide treatment on grass biomass at 45 DAS each year, but not on biomass of the other weeds and total weed biomass (Tables 8 and 9). The effect of the stale seedbed treatments on weed biomass was inconsistent across treatments and years. The stale seedbed with tillage had a lower biomass of grass weeds than without a stale seedbed and no post sowing herbicide in 2014, but there was no benefit of the stale seedbed with tillage when pendimethalin and/or bispyribac were used.

### Table 3

Effect of seedbed and post sowing herbicide treatments on weed density in dry-seeded rice at 20 days after sowing (DAS).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Weed density at 20 DAS (plants m(^{-2}))</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grasses</td>
<td>Broad-leaves</td>
<td>Sedges</td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>83a</td>
<td>25a</td>
<td>35a</td>
</tr>
<tr>
<td>Stale seedbed with glyphosate</td>
<td>40b</td>
<td>12b</td>
<td>17b</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>27c</td>
<td>13b</td>
<td>23b</td>
</tr>
<tr>
<td>Post sowing herbicide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unsprayed check</td>
<td>99a</td>
<td>26a</td>
<td>28a</td>
</tr>
<tr>
<td>Pendimethalin 0.750 kg ha(^{-1})</td>
<td>1b</td>
<td>8b</td>
<td>22a</td>
</tr>
<tr>
<td>Interaction</td>
<td>5</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

\* Data were square-root transformed before analysis; however, back-transformed actual mean values are presented based on the interpretation from the transformed values.

### Table 4

Interaction effect of seedbed and post sowing herbicide treatments on grass weeds and total weed density in dry-seeded rice at 20 DAS.

<table>
<thead>
<tr>
<th>Seedbed/Post sowing herbicide</th>
<th>Weed density at 20 DAS (plants m(^{-2}))</th>
<th>2014</th>
<th>2015</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grasses</td>
<td>Broad-leaves</td>
<td>Sedges</td>
<td>Total weeds</td>
<td>Grasses</td>
</tr>
<tr>
<td>Unsprayed check</td>
<td>12.9 (166)</td>
<td>1.0 (0)</td>
<td>14.4 (208)</td>
<td>2.9 (9)</td>
<td>15.4 (238)</td>
</tr>
<tr>
<td>Pendimethalin 0.750 kg ha(^{-1})</td>
<td>8.8 (76)</td>
<td>2.0 (3)</td>
<td>10.5 (111)</td>
<td>3.6 (14)</td>
<td>10.9 (118)</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>7.4 (55)</td>
<td>1.0 (0)</td>
<td>10.4 (109)</td>
<td>3.0 (10)</td>
<td>10.0 (101)</td>
</tr>
<tr>
<td>LSD (p = 0.05)</td>
<td>0.9</td>
<td>0.8</td>
<td>1.3</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>
Table 5

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Weed density (plants m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Seedbed alone</td>
<td></td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>10a</td>
</tr>
<tr>
<td>Stale seedbed with glyphosate</td>
<td>10b</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>8a</td>
</tr>
<tr>
<td>Post sowing herbicide</td>
<td></td>
</tr>
<tr>
<td>Unsprayed check</td>
<td>18a</td>
</tr>
<tr>
<td>Pendimethalin 0.75 kg ha(^{-1})</td>
<td>4c</td>
</tr>
<tr>
<td>Bispyribac sodium 0.025 kg ha(^{-1})</td>
<td>1d</td>
</tr>
<tr>
<td>Pendimethalin 0.750 kg fb bispyribac sodium 0.025 kg ha(^{-1})</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Interaction: S, S, S, S, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS

1 Data were square-root transformed before analysis, however back-transformed actual mean values are presented based on the interpretation from the transformed values.
2 Means presented within each column with no common letter(s) are significantly different according to Tukey’s test where \(p < 0.05\); S – significant; NS – non-significant.

In 2015, the stale seedbed with tillage reduced grass weed biomass in treatments in which pendimethalin was used, in addition to the treatment with no post sowing herbicide (Table 9). The stale seedbed with glyphosate did not reduce grass weed biomass in comparison with no stale seedbed in the check treatment in 2014, increased weed biomass when followed by pendimethalin, and reduced weed biomass when followed by bispyribac alone. In 2015, the stale seedbed with glyphosate reduced weed biomass in combination with all post sowing herbicide treatments except pendimethalin fb bispyribac, in comparison with no stale seedbed. Averaged over the two years, the stale seedbed with tillage decreased grass weed biomass by 36% in comparison with no stale seedbed, and by 17% in comparison with the stale seedbed with glyphosate.

In both years, the stale seedbed with tillage significantly reduced broadleaf and total weed biomass in comparison with no stale seedbed, and reduced sedge biomass by 22% in 2015 (Table 8). The stale seedbed with glyphosate had no effect on biomass of broadleaves, sedges and total weeds in 2014 in comparison to no stale seedbed, but reduced sedge and total weed biomass in 2015. The stale seedbed with tillage was more effective than the stale seedbed with glyphosate in reducing grass, broadleaf and total weed biomass in 2014, and broadleaf biomass in 2015. Both stale seedbed methods were equally effective in reducing grass, sedge and total weed biomass in 2015.

All post sowing herbicide treatments significantly reduced broadleaf and total weed biomass in both years in comparison with the unsprayed check, and the treatments with bispyribac (alone or following pendimethalin) significantly reduced sedge biomass each year (Table 8). Sequential application of pendimethalin and bispyribac was the most effective weed control treatment for grass, broadleaf and total weed biomass, and decreased grass weed biomass by 94–98% (Tables 8 and 9). Each year, this treatment also had a lower biomass of grass, broadleaf and total weeds than the use of each of these herbicides alone. Pendimethalin was superior to bispyribac for the control of grass weeds, but bispyribac was more effective on sedges in both years.

3.5. Grain and straw yield

There was a significant interaction between seedbed treatment and post sowing herbicide treatment on both grain and straw yield each year (Table 10). The response to stale seedbed treatment varied with post sowing herbicide treatment. In the absence of post sowing herbicides, the stale seedbed with tillage increased grain yield from 0.7–1.0 t ha\(^{-1}\) to 2.1–2.5 t ha\(^{-1}\), while the stale seedbed with glyphosate only increased grain yield in 2015. The post sowing combination of pendimethalin fb bispyribac produced significantly higher grain yield, regardless of seedbed treatment. Each year, grain yield was the highest with the combination of the stale seedbed with tillage and pendimethalin fb bispyribac. The stale seedbed with glyphosate and pendimethalin fb bispyribac treatment did not increase grain yield in comparison with no stale seedbed and pendimethalin fb bispyribac in either year. Grain yields with pendimethalin alone were significantly higher (by 1.9–2.3-fold) than with no pendimethalin, regardless of seedbed treatment. Grain yields with bispyribac alone and without a stale seedbed were, however, similar to yield of the stale seedbed with tillage and no post sowing herbicide in 2014, and of the stale seedbed with glyphosate and no post sowing herbicide in 2015. Treatment effects on straw yield were generally similar to effects on grain yield.

3.6. Economics

All treatment combinations gave positive returns except the combination of no stale seedbed and no post sowing herbicide each year, and the stale seedbed with glyphosate and no post sowing herbicide in 2014 (Table 11). The combination of a stale seedbed with tillage and pendimethalin fb bispyribac gave the highest economic returns ($1290–1330 ha\(^{-1}\)) and the stale seedbed with glyphosate fb pendimethalin gave the lowest economic returns ($823–864 ha\(^{-1}\)). The profitable $200–320 ha\(^{-1}\) was significantly higher than when...
these herbicides were used without a stale seedbed, and $240–330\text{ ha}^{-1}$ higher than when used with the stale seedbed with glyphosate treatment. The treatment combination of the stale seedbed with glyphosate and pendimethalin fb bispyribac had lower or similar economic returns to pendimethalin fb bispyribac without a stale seedbed.

### 4. Discussion

#### 4.1. The use of a stale seedbed and/or post sowing herbicides will deplete the soil weed seedbank

The viable seedbank of *E. colona* and *D. aegyptium* at the time of rice sowing was lower in the stale seedbed treatments than without a stale seedbed. This was probably because the first irrigation of the stale seedbed enhanced weed seedling emergence, and the emerged weeds were then destroyed by glyphosate or tillage. At the time of harvest, the seedbank of these two weed species was reduced in both stale seedbed treatments in comparison with no stale seedbed, and by more in the stale seedbed with tillage than with glyphosate in the second year. The lower seedbank of both grass weeds under a stale seedbed with tillage than with glyphosate is probably due to kill of both emerged and still to emerge weed seedlings by shallow tillage (Egley and Williams, 1978; Sprankle et al., 1975). However, the stale seedbeds did not deplete the seedbank of either grass weed at the time of harvest in comparison with the initial weed seedbank.

The sequential application of pendimethalin and bispyribac reduced the seedbank at harvest by around 50% in comparison with the initial seedbank, suggesting that sequential application of these herbicides will reduce the weed seedbank over time. However, the weed seedbank was not reduced when pendimethalin was used alone, nor in 2015 when bispyribac was used alone. Sequential application of the two herbicides provided better control of weeds which was reflected in the reduction in weed seedbank from sowing to harvest. The higher seedbank of *D. aegyptium* under bispyribac alone is consistent with other observations of poor control of this weed by this herbicide (Bhullar et al., 2016a). These results suggest that a stale seedbed and post sowing herbicides could substantially reduce the viable seedbank at rice sowing, providing competitive advantage to the crop during its early stages of growth. However, the non-significant interaction between seedbed and post sowing herbicide treatments indicated that there was no advantage of combining seedbed treatments with post sowing herbicides on the weed seedbank at harvest. The higher seedbank after crop harvest than the initial seedbank in some treatments could be due to seed production by weeds that survived a stale seedbed and/or post sowing herbicide treatment, or by weeds that emerged after herbicide application. This may also explain the higher weed density and biomass in 2015 than 2014. This highlights the importance of removing (hand-weeding) late emerged weed plants before they set seed, in order to reduce weed seedbank and infestation over time. The initial seedbank of both the weed species in 2015 under all weed control treatments was similar which might be due to tillage bringing new seeds from depth into the germinating zone of the soil. Whether continuous use of stale seedbeds for DSR would reduce the weed seedbank over time needs further investigation.

#### 4.2. The use of a stale seedbed with glyphosate or shallow tillage is equally effective in controlling weeds in the DSR

Weed density at 20 DAS showed that a stale seedbed with tillage or glyphosate was able to significantly suppress weed establishment relative to that without a stale seedbed with no post sowing herbicide. At this stage, the efficacy of both stale seedbed methods was similar for all three weed groups and total weeds. The stale seedbed with tillage continued to show lower density of grass weeds especially of aerobic grasses such as *D. aegyptium*, *D. sanguinalis* and *E. indica* until 45 DAS than without a stale seedbed in both years, in the absence of post sowing herbicides. At 45 DAS, the stale seedbed with tillage was again effective in suppressing all weed groups and total weeds each year. However, in 2014, the stale seedbed with glyphosate was ineffective in reducing weed density of *D. sanguinalis*, and less effective than the stale seedbed with tillage in reducing weed density of *D. arvensis*. In the absence of post sowing herbicides, it was also ineffective in suppressing *D. aegyptium* in 2014. These results differ from those of Riemens et al.

<table>
<thead>
<tr>
<th>Seedbed/Post sowing herbicide</th>
<th>Echinochloa colona density at 45 DAS (plants m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td>CHK</td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>4.79 (22)</td>
</tr>
<tr>
<td>Stale seedbed with glyphosate</td>
<td>4.24 (17)</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>3.93 (15)</td>
</tr>
<tr>
<td>LSD (p = 0.05)</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Data were square root transformed before analysis, parentheses are back-transformed actual mean values.

<table>
<thead>
<tr>
<th>Seedbed/Post sowing herbicide</th>
<th>Dactyloctenium aegyptium density at 45 DAS (plants m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td>CHK</td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>4.53 (20)</td>
</tr>
<tr>
<td>Stale seedbed with glyphosate</td>
<td>4.11 (16)</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>3.90 (14)</td>
</tr>
<tr>
<td>LSD (p = 0.05)</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Data were square root transformed before analysis, parentheses are back-transformed actual mean values.
(2007) who reported higher efficacy of the stale seedbed with glyphosate and of Renu et al. (2000) with paraquat than with mechanical cultivation. They pointed out that herbicides kill weeds without bringing new seeds to the germination zone in the soil. In the present study, some weed seedlings might have escaped because they emerged after glyphosate application whereas shallow tillage would have killed all weed seedlings above and below the soil surface.

Greater density of grasses, broadleaves and sedges in 2015 than 2014 may be related to the build-up of their soil seedbank under all treatments (Table 1). A field survey of farmer fields in Punjab also showed a shift in weed flora towards these aerobic grass weeds under continuous DSR (Bhullar et al., 2018).

Reduction in density of C. rotundus by the stale seedbed treatments (22–51%) indicated their partial success in reducing competitive effects on rice. Lower grass weed density under both stale seedbed treatments (42–67%) than without a stale seedbed (83–108 plants m⁻²) could be related to the depletion of their seedbank before sowing of rice, as initial weed population has been shown to be directly related to the size of their seedbank before sowing of rice, as in- 

4.3. The combination of a stale seedbed and post sowing herbicides will be more effective in controlling weeds and increasing yield in comparison with the use of post sowing herbicides alone

4.3.1. Weed control

The stale seedbed with tillage conferred some additional benefits to weed control when used with pendimethalin fb bispyribac, in comparison with use of these herbicides with no stale seedbed. While there was no additional benefit from use of a stale seedbed when combined with pendimethalin fb bispyribac on total weed density, and density of some weed species at 45 DAS, the use of stale seedbed with tillage combined with pendimethalin fb bispyribac reduced density of D. aegyptium in both years, and of E. colona in 2015. Similarly, in terms of weed biomass also, there was no additional advantage of stale seedbed on biomass of broadleaves, sedges and total weed biomass in either year when combined with pendimethalin fb bispyribac, but the stale seedbed with tillage reduced grass weed biomass in 2015.

Pendimethalin, primarily a grass weed killer, was able to effectively reduce the population of grass weeds under all seedbed treatments which indicates the importance of this herbicide in DSR systems. While bispyribac was able to provide some control of C. rotundus, the considerable increase in plant density in 2015 compared with 2014 in all seedbed treatments points to the need for alternative herbicide options for this weed. Sequential applications of pendimethalin and bispyribac, due to their different weed control spectra, provided superior control of the diverse weed flora than when the herbicides were used separately. Bispyribac provides effective control of typical rice grass weeds such as E. colona (Chauhan, 2011), however, it is weak against aerobic grass weeds such as D. aegyptium and Leptochloa chinensis (Bhullar et al., 2016a) which are effectively controlled by pendimethalin (Kumar and Kundra, 2001).

### Table 8
Effect of seedbed and post sowing herbicide treatments on weed biomass in dry-seeded rice at 45 DAS.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Weed biomass (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td>Grasses</td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>22a</td>
</tr>
<tr>
<td>Stale seedbed with glyphosate</td>
<td>20a</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>15b</td>
</tr>
<tr>
<td>Post sowing herbicide</td>
<td>Unsprayed check</td>
</tr>
<tr>
<td>Pendimethalin 0.750 kg ha⁻¹</td>
<td>5c</td>
</tr>
<tr>
<td>Bispyribac sodium 0.025 kg ha⁻¹</td>
<td>18b</td>
</tr>
<tr>
<td>Pendimethalin 0.750 kg ha⁻¹ fb bispyribac sodium 0.025 kg ha⁻¹</td>
<td>1d</td>
</tr>
<tr>
<td>Interaction</td>
<td>S</td>
</tr>
</tbody>
</table>

* Data were square-root transformed before analysis, however back-transformed actual mean values are presented based on the interpretation from the transformed values.
* Means presented within each column with no common letter(s) are significantly different according to Tukey’s test where p ≤ 0.05; S-significant; NS—non significant; fb—followed by.

4.3.2. Grain yield

The results support the hypothesis that use of a stale seedbed in combination with pendimethalin fb bispyribac will confer additional benefit on grain yield in the case of the stale seedbed with tillage. Use of the stale seedbed with tillage gave significantly higher grain yield that with no stale seedbed when both were combined with pendimethalin fb bispyribac. However, use of the stale seedbed with glyphosate with pendimethalin fb bispyribac did not increase yield. There was a stronger negative relationship (p < 0.0001) between rice grain yield

### Table 9
Interaction effect of seedbed and post sowing herbicide treatments on grass weed biomass at 45 days after sowing dry-seeded rice.

<table>
<thead>
<tr>
<th>Seedbed/Post sowing herbicide</th>
<th>Grass weed biomass at 45 DAS (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td>CHK</td>
</tr>
<tr>
<td>Without stale seedbed</td>
<td>7.93 (63)</td>
</tr>
<tr>
<td>Stale seedbed with glyphosate</td>
<td>7.46 (55)</td>
</tr>
<tr>
<td>Stale seedbed with tillage</td>
<td>6.20 (38)</td>
</tr>
<tr>
<td>LSD (p = 0.05)</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Relationship between total weed biomass at 45 DAS and rice grain yield in 2015.

The higher rice grain yield in the combination of pendimethalin and bispyribac than their use singly was associated with superior broad-spectrum weed control, which was reflected in increased crop biomass and panicle production. The combination of the stale seedbed with tillage, pendimethalin and bispyribac provided low weed competition environment for the crop, which resulted in the highest grain yield and also the highest economic returns.

The stale seedbed with tillage decreased the grass weed seedbank before sowing of rice by > 25% compared to no stale seedbed, which significantly decreased in-crop weed density and biomass which increased grain yield. Even though C. rotundus densities were similar (in 2014) or greater than grass weeds (in 2015), it produced lower shoot biomass than the grass weeds (Tables 5 and 8). C. rotundus plants are much smaller, tend to grow straight, and are likely to be less competitive with rice crop than grass weeds. In contrast, grass weeds such as E. colona and D. aegyptium are taller, produce greater biomass and are more competitive with the crop. Hence even at lower densities grass weeds cause greater crop yield losses than small statured sedges. This difference in competitive ability between grass weeds and sedges could be the reason for higher rice grain yield under the stale seedbed with tillage, even though C. rotundus density was still high. This could also be the reason for lower crop yield under sole application of bispyribac, which gave good control of C. rotundus, E. colona and D. aegyptium, while D. aegyptium and E. indica flourished and competed with the crop. In this study, C. rotundus density increased by 2.2–2.3-fold from 2014 to 2015 without a stale seedbed and with the stale seedbed with glyphosate, and by 1.6-fold in the stale seedbed with tillage. These results indicate that a stale seedbed is not very effective against C. rotundus and this tactic needs to be integrated with effective in-crop herbicides. Further studies on the modifications to the stale seedbed and its integration with herbicide mixtures of glyphosate and residual herbicides and with improved spray technology are needed especially for situations with highly diverse weed flora and where perennial weeds such as C. rotundus are a serious problem.

In this study, the benefits from additional grain yield under combined adoption of the stale seedbed and two in-crop herbicides exceeded the extra input costs incurred including an additional irrigation, cultivation and herbicides. It needs to be emphasised that the attraction of DSR to local farmers in Indian states of Punjab and Haryana is primarily associated with the mechanisation of rice sowing because of the unavailability and high cost of manual labour for transplanting of conventional puddled rice. These results also highlight the need for appropriate integration of herbicides. When the stale seedbed with tillage was practised with a single herbicide, which achieved partial control of weed flora, economic returns were decreased by > $ 765 ha$^{-1}$ compared with combination of the stale seedbed with tillage and sequential use of two herbicides that provided broad-spectrum weed control. Even though DSR with alternate wetting and drying water management offers significant irrigation water savings over PTR, it is not the primary driver of DSR adoption. In previous research at this site, Sudhir-Yadav et al. (2011) showed 33–53% reduction in irrigation and weed biomass at 45 DAS (Figs. 3 and 4) which explains the differential grain yield under different weed control treatments. The relationship was slightly stronger in 2015 ($R^2 = 0.89$) than in 2014, the dry season ($R^2 = 0.79$).

Fig. 3. Relationship between total weed biomass at 45 DAS and rice grain yield in 2014.

Fig. 4. Relationship between total weed biomass at 45 DAS and rice grain yield in 2015.
water use of DSR in comparison with PTR irrigated using alternate wetting and drying. Hence, the use of an extra irrigation (7.5 cm depth) for a stale seedbed still allows considerable irrigation water saving in DSR in comparison with PTR.

5. Conclusions

The stale seed bed treatments significantly decreased the viable seedbank of *E. colona* and *D. aegyptium* at rice sowing compared with no stale seedbed. The combination of the stale seedbed with tillage, and in-crop use of pendimethalin followed by bispyribac-sodium provided the highest rice grain yield and economic returns. Thus, benefits from additional grain yield under combined adoption of the stale seedbed and sequential post sowing herbicides treatment far exceeded the extra cost of one additional irrigation, additional cultivation and herbicides than DSR without a stale seedbed.

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References


