Weed Management in Dry-Seeded Fine Rice under Varying Row Spacing in the Rice-Wheat System of Punjab, Pakistan

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Abstract: Direct seeding can curtail water and labor inputs involved in rice production; nevertheless, its large-scale adoption is impeded by heavy weed infestation. A field study was undertaken in 2011 and 2012 to evaluate the effects of crop row spacing (20 and 10 cm) and postemergence herbicides on weed growth and yield of dry-seeded rice. As a herbicide, pyrazosulfuron ethyl at 30 g ha⁻¹, bipyribac-sodium at 30 g ha⁻¹, or penoxsulam at 15 g ha⁻¹ was applied (15 days after sowing, DAS) alone or in combination with fenoxaprop-p-ethyl at 86.25 g ha⁻¹ subsequently (30 DAS). In addition, a partial weedy plot (manually weeded once at 28 DAS), and a weed-free plot were established for each row spacing. In the partial weedy plot with 10-cm row spacing, the weed density was only 21 and 25% lower than that in the plot with 20-cm row spacing in 2011 and 2012, respectively. The sole application of an early postemergence herbicide restricted weed growth, while subsequent application of fenoxaprop as late postemergence application suppressed weed growth further, the magnitude of suppression being more pronounced in the plot with narrow row spacing. The density and biomass of weeds were lowest in the plot with 10-cm row spacing applied bipyribac-sodium followed by fenoxaprop. Under weed-free conditions, yields were 29% higher in the plot with 10-cm row spacing (4.18 t ha⁻¹) than in that with 20-cm row spacing (3.23 t ha⁻¹). Grain yield in the herbicide-treated plots was 87 – 188% higher than that in the partial weedy plots. These results suggested that narrow row spacing and sequential herbicide application can help tackle recalcitrant weed flora in dry-seeded rice fields.

Key words: Asia, Dry seeding, Herbicides, Rice yield, Weed control, Weed growth.
direct seeding. Nevertheless, indiscriminate use of herbicides is driving agroecosystems toward declining species diversity and, in many situations, is leading to herbicide resistance (Powles and Yu, 2010). Singh (2008) found that the continuous use of a single herbicide can produce quantitative changes in weed community composition in just 5 years. Currently available rice herbicides have a narrow spectrum of activity and their efficacy is further limited when they are used alone (Singh, 2008; Chauhan, 2012). This rarely provides season-long weed control (Khaliq et al., 2011a, b). Herbicide tank mixtures or their sequential applications have been suggested as an alternative to overcome this issue (Khaliq et al., 2011a, 2012a, b). The adoption and execution of an integrated approach of available weed management practices have been advocated to combat weed menaces in DSR and prevent any change in weed community structure (Maity and Mukherjee, 2008).

In modern agriculture, field crops, especially the cereals, are planted in distinct rows with variable row spacing and plant densities (Chen et al., 2008). Manipulation of crop row spacing and its orientation has been suggested as a mean to reduce light interception by weeds (Chauhan, 2012). Sowing crops in narrow rows gives them a competitive edge over weeds due primarily to early and rapid canopy closure. Chauhan and Johnson (2011) reported 34% greater weed biomass in a 30-cm-spaced rice crop than in a 15-cm-spaced crop and concluded that the critical period was also less for the latter.

In conventional transplanted rice, a plant-to-plant distance of 22.5 cm is maintained and weeds are mostly controlled by the flooded environment. Sometimes, butachlor or acetachlor is applied within 3 – 7 days following transplanting. Direct seeding of rice is at its infant stage in Pakistan and development of an integrated and sustainable weed management options remains a major challenge to the widespread adoption of this resource conservation technology. Ever-changing climatic conditions have led to a variable weed flora that is further modified when row spacing is altered. We hypothesized that efficient weed management in DSR can be achieved through the use of narrow row spacing and sequential herbicide applications. Our study aims to explore a suitable combination of row spacing and herbicides for weed management in DSR.

Materials and Methods

1. Site description

This study was conducted at the Agronomic Research Farm, University of Agriculture, Faisalabad, Pakistan (31.25°N, 73.09°E, 184 m above sea level). The soil of the experimental site belongs to the Lyallpur soil series (Aridisol-fine-silty, mixed, hyperthermic Ustalfic, Haplargid in the USDA classification and Haplic Yermosols in the FAO classification). The pH of the saturated soil and total soluble salts were 7.7 and 0.79 dS m⁻¹, respectively. Organic matter, total nitrogen, available phosphorus, and potassium were 0.74%, 0.055%, 7.1 ppm, and 183 ppm,
respectively. Because of high evapotranspiration, Faisalabad features an arid climate with a mean annual rainfall of about 200 mm. The meteorological data during the course of crop growth are presented in Fig. 1.

2. Experimental details

The experiments were conducted during the summer seasons of 2011 and 2012. Seeds of popular rice cv. Super basmati were obtained from the Rice Research Institute, Kala Shah Kaku, Sheikhupura. It is an extra-long-grain (11.2 mm kernel length and 1.7 mm kernel breadth) aromatic fine rice cultivar. Because of its strong aroma, it fetches a higher price in the global market than the other basmati cultivars. This cultivar was selected as a test crop because it is the predominant basmati cultivar in the rice-wheat cropping system of Punjab, Pakistan (Erenstein, 2010), and has shown weed competitiveness in DSR (Khaliq and Matlaboo, 2011). The soil was cultivated 3 times with a tractor-mounted cultivator and followed each time by planking to prepare a fine seedbed. A basal fertilizer dose of 42 kg N, 55 kg P$_2$O$_5$, and 40 kg K$_2$O ha$^{-1}$ was applied in the form of urea (46% N), diammonium phosphate (18% N and 46% P$_2$O$_5$), and sulfate of potash (50% K$_2$O), respectively. The whole phosphorus and potassium and one-third of N were applied at the time of sowing. The remaining N (83 kg) was top-dressed in two equal splits: at tillering (30 days after sowing, DAS) and at panicle initiation (65 DAS). Seeds were subjected to osmo-hardening for 48 hr with aerated 2.2% calcium chloride solution (osmotic potential of –1.25 MPa) prior to sowing.

The ratio of seed weight to soaking solution volume was presented as t ha$^{-1}$ after adjustment to 14% moisture content.

Data on weeds (density and biomass) for each experimental unit were recorded from two randomly selected quadrats (40 × 40 cm) at 45 DAS. Weeds were counted and clipped above the ground surface. They were dried in an oven at 70°C for 72 hr and biomass was then recorded. Panicle-bearing tillers (m$^{-2}$) were counted in three randomly selected places in each plot. At physiological maturity, tillers were harvested from plots sown in 5 and 10 rows each 5 m in length spaced 20- and 10-cm apart, respectively. Tillers in each experimental plot were manually threshed to determine grain yield, which was presented as t ha$^{-1}$ after adjustment to 14% moisture content.

3. Observations and statistical analyses

Data on weeds (density and biomass) for each experimental unit were recorded from two randomly selected quadrats (40 × 40 cm) at 45 DAS. Weeds were counted and clipped above the ground surface. They were dried in an oven at 70°C for 72 hr and biomass was then recorded. Panicle-bearing tillers (m$^{-2}$) were counted in three randomly selected places in each plot. At physiological maturity, tillers were harvested from plots sown in 5 and 10 rows each 5 m in length spaced 20- and 10-cm apart, respectively. Tillers in each experimental plot were manually threshed to determine grain yield, which was presented as t ha$^{-1}$ after adjustment to 14% moisture content.

The data collected were subjected to Fisher’s analysis of variance and the Tukey’s honest significance difference test (HSD) at $P ≤ 0.05$ was employed to compare treatment means (Statistix 8.1, Analytical software, Statistix; Tallahassee, FL, USA, 1985-2003). Statistical analyses revealed that the year effect was significant and hence data are presented separately for two years. Data on weed density and biomass were transformed; however, square root transformation did not improve variance homogeneity. Therefore, nontransformed data were used for further statistical analyses. Graphical representation of the data was carried out using MS-Excel (Microsoft Corporation, USA) and, to ascertain the relationship among different variables, linear regression analyses were also done using the same program.

Results

Weed flora of the experimental site consisted of Triandema portulacastrum L., Portulaca oleracea L., and Alternanthera philoxeroides (Mart.) Griseb as broad-leaved weeds; Dactylotenium aegyptium (L.) Willd., Eleusine indica (L.) Gaertn., Echinochloa colona, Echinochloa crus-galli (L.) P. Beauv., Leptochloa chinensis (L.) Nees, and Cynodon dactylon SC, Arysta Life Sciences, Karachi, Pakistan), or penoxsulam at 15 g ai ha$^{-1}$ (Ryzelan 240 SC, Arysta Life Sciences, Karachi, Pakistan) was applied alone as early postemergence application (15 DAS) or in combination with a late postemergence application (30 DAS) of fenoxaprop p-ethyl (with a safener) at 86.25 g ai ha$^{-1}$ (Puma Super 7.5EW, Bayer Crop Sciences, Karachi, Pakistan). Spraying was done using a knapsack sprayer fitted with a flat-fan nozzle at a spray pressure of 210 kPa. The volume of spray (350 L ha$^{-1}$) was calibrated using water. Partial weedy and weed-free plots were also included for comparison. Partial weedy plots were weeded manually once at 28 DAS to avoid complete crop failure and weeds were allowed to grow after that. In weed-free plots, all emerged weed seedlings were removed manually or with a hoe until 75 DAS (7 times).
(L.) Pers. as grassy weeds; and *Cyperus rotundus* L. and *C. iria* L. as sedge weeds during both years. A new grassy weed, *Digitaria ciliaris* (Retz.) Koel., was observed only in the second year of the study. The dominant weeds were *T. portulacastrum*, *D. aegyptium*, and *E. indica*. However, total weed density and biomass are presented in this section.

A significant (*P* ≤ 0.05) interaction between row spacing and weed control treatments was observed for weed density (Table 1, Fig. 2). In the partial weedy plots, weed density was 361 and 443 plants m\(^{-2}\) with 20-cm row spacing and 285 and 332 plants m\(^{-2}\) with 10-cm row spacing in 2011 and 2012, respectively. Nonetheless, weed density in these plots was still manifold higher than that in the herbicide-treated plots (Fig. 2). In the partial weedy plots with 10-cm row spacing, weed density was only 21 and 25% lower than that in the plots with 20-cm row spacing in the 2011 and 2012, respectively. Both sole and sequential herbicide applications proved quite effective in averting weed density as compared with the partial weedy plots in both years. When applied alone, bispyribac-sodium gave the lowest weed count and appeared superior to pyrazosulfuron and penoxsulam (Fig. 2). Nevertheless, certain weeds, including *D. aegyptium*, *E. indica*, *L. chinensis*, and *C. rotundus*, still persisted in these plots (data not shown). However, herbicide performance was strongly influenced by row spacing. Weed density in bispyribac-sodium-treated plots was 74 and 49 plants m\(^{-2}\) in 2011 and 87 and 72 plants m\(^{-2}\) in 2012 with 20- and 10-cm row spacing, respectively. Although the sole application of an early postemergence herbicide restricted weed density in DSR, greater suppression was observed when these were sequentially followed by a late postemergence application of fenoxaprop and the effect was more pronounced by narrowing the row spacing. Bispyribac-sodium followed by fenoxaprop gave the lowest weed density in the plot with 10-cm row spacing and was statistically similar (*P* ≤ 0.05) when penoxsulam was followed by fenoxaprop, the trend being consistent in both years in the plots with either row spacing (Fig. 2).

![Fig. 2. Influence of weed control treatments (WC, partial weedy check; Pyraz., pyrazosulfuron; Bisp., bispyribac-sodium; Penox, penoxsulam; Pyraz. fb Fenox., pyrazosulfuron followed by fenoxaprop; Bisp. fb Fenox., bispyribac-sodium followed by fenoxaprop; Penox. fb Fenox., penoxsulam followed by fenoxaprop) on weed density (no. m\(^{-2}\)) in dry-seeded fine rice sown at 10- and 20-cm row spacing. Capped bar denotes HSD value at 5% probability level.](image)

A significant (*P* ≤ 0.05) interactive effect between row spacing and weed control treatments was also evident for weed biomass (Table 1, Fig. 3). Maximum weed biomass was recorded in partial weedy plots under both row spacings. Weed biomass was 267 and 315 g m\(^{-2}\) in the plots with 10-cm row spacing compared with 363 and 414 g m\(^{-2}\) in the plots with 20-cm row spacing in 2011 and 2012, respectively (24 – 27% less biomass in the narrow row spacing). The postemergence application of any one of the 3 herbicides gave a lower weed biomass than in the partial weedy plots, yet the sequential herbicide application gave an even lower weed biomass (Fig. 3). In both seasons, minimum (*P* ≤ 0.05) weed biomass was obtained after the

*Table 1. Analysis of variance for the influence of row spacing (RS) and weed control treatments (WC), and their interaction (RS × WC) on weed density, dry biomass, rice panicles, and grain yield.*

| Source of variation | Degrees of freedom | Weed density (2011) | Weed density (2012) | Weed biomass (2011) | Weed biomass (2012) | Panicles (2011) | Panicles (2012) | Grain yield (2011) | Grain yield (2012) |
|---------------------|--------------------|--------------------|--------------------|--------------------|--------------------|----------------|----------------|--------------------|--------------------|
| Replication         | 2                  | Yes                | Yes                | Yes                | Yes                | Yes            | Yes            | Yes                | Yes                |
| RS                  | 1                  | < 0.001            | < 0.001            | < 0.001            | < 0.001            | < 0.001        | < 0.001        | < 0.001            | < 0.001            |
| WC                  | 6 / 7*             | < 0.001            | < 0.001            | < 0.001            | < 0.001            | 0.702          | 0.263          | 0.133              | 0.001              |
| RS × WC             | 6 / 7*             | < 0.001            | < 0.001            | 0.702              | 0.263              | 0.133          | 0.001          |                    |                    |
| Error               | 26 / 30*           |                    |                    |                    |                    |                |                |                    |                    |

* Degree of freedom for panicle number and grain yield.
application of bispyribac-sodium or penoxsulam followed by fenoxaprop in the plots with a 10-cm row spacing that was statistically similar to that observed in the plots with a 20-cm row spacing in the same weed control treatment.

The number of rice panicles was significantly \((P \leq 0.05)\) affected by row spacing and herbicide treatments (Table 1, Fig. 4) and the interactive effect between the treatments was not significant. Rice panicles were 14 and 15% more numerous in the plots with a 10-cm row spacing than 20-cm row spacing (averaged across weed control treatments) in 2011 and 2012, respectively. Irrespective of row spacing, partial weedy plots gave the lowest \((P \leq 0.05)\) number of panicles in 2011 (133 m^{-2}) and 2012 (125 m^{-2}), which was substantially lower than the number of panicles obtained in the weed-free and herbicide-treated plots. Weed-free plots had 184 and 226% more panicles than partial weedy plots in 2011 and 2012, respectively. Moreover, herbicide treatments, whether sole or sequential, also had fewer panicles per unit area than weed-free treatments in both years (Fig. 4). The number of rice panicles was negatively associated with weed density (Fig. 5) and weed biomass (Fig. 6). In both years, regression analysis revealed more than 70% reduction in rice panicle number owing to weed density, regardless of row spacing (Fig. 5). Likewise, up to 82 and 79% and 79 and 74% of the reduction in rice panicle number in 2011 and 2012, respectively, was explained by weed biomass in crops sown in 20- and 10-cm-
Fig. 5. The relationship between number of panicles (no. m$^{-2}$) and weed density (no. m$^{-2}$) in dry-seeded fine rice sown at 10- and 20-cm row spacing in (a) 2011 and (b) 2012. ** denotes significance at the 0.01 probability level.

Fig. 6. The relationship between number of panicles (no. m$^{-2}$) and weed biomass (g m$^{-2}$) in dry-seeded fine rice sown at 10- and 20-cm row spacing in (a) 2011 and (b) 2012. ** and *** denote significance at the 0.01 and 0.001 probability levels, respectively.
spaced rows, respectively (Fig. 6).

Rice grain yield was affected \((P \leq 0.05)\) only by row spacing and herbicide treatments in 2011; however, their interactive effect was significant \((P \leq 0.05)\) in 2012 (Table 1). In 2011, grain yield was 16% higher in the plots with a 10-cm row spacing than 20-cm row spacing (Fig. 7). Minimum grain yield (1.14 t ha\(^{-1}\)) was observed in the partial weedy plots. Grain yield was 214% higher in the weed-free plots than in the partial weedy plots in 2011. Grain yield was 87 – 188% higher in the herbicide-treated plots than in the partial weedy plots, but was still 18 – 40% lower than that in the weed-free plots. Irrespective of crop row spacing, bispyribac-sodium followed by fenoxaprop gave the highest rice grain yield (3.3 t ha\(^{-1}\)) among the herbicide treatments in 2011. Grain yield in the partial weedy plots with 10-cm row spacing (1.3 t ha\(^{-1}\)) was 45% more than that in the plots with 20-cm row spacing (0.9 t ha\(^{-1}\)) in 2012. Under weed-free conditions, the yield increment was greater (29%) in 10-cm row spacing (4.2 t ha\(^{-1}\)) than in 20-cm spacing (3.2 t ha\(^{-1}\)). In 2012, maximum grain yield (3.5 t ha\(^{-1}\)) was obtained by treatment with bispyribac-sodium followed by fenoxaprop in the plots with 10-cm row spacing, while the same treatment gave a grain yield of 2.9 t ha\(^{-1}\) in the plots with 20-cm row spacing (Fig. 7). Rice grain yield was also negatively associated with weed density (Fig. 8) and weed biomass (Fig. 9). Nevertheless, such an association was slightly stronger for wider row spacing (20 cm). Regression analysis explained over 70 – 91% of the variation in grain yield owing to weed density and weed biomass in both years. Irrespective of row spacing, rice grain yield was strongly correlated with rice panicle number per unit area and panicle number accounted for over 90% of the variation in rice grain yield at harvest (Fig. 10).

**Discussion**

Our study evaluated the influence of row spacing and herbicide treatments on weed growth and rice yield. The local climate and soil moisture regimes of the experimental site favored weed diversity as well as their growth, primarily because the fields were not submerged in water. Weeds, such as *T. portulacastrum*, that otherwise are nonnative to lowland rice fields, as well as those that are normally controlled by flooding in transplanted rice, were in abundance in our study. The greater weed pressure in DSR is mainly attributed to a mere absence of flooding, dry tillage, and alternate wetting and drying during crop establishment (Chauhan, 2012).

The results of our study clearly demonstrated the effectiveness of narrow row spacing in averting high weed...
Fig. 8. The relationship between grain yield (t ha\(^{-1}\)) and weed density (no. m\(^{-2}\)) in dry-seeded fine rice sown at 10- and 20-cm row spacing in (a) 2011 and (b) 2012. ** and *** denote significance at the 0.01 and 0.001 probability levels, respectively.

Fig. 9. The relationship between grain yield (t ha\(^{-1}\)) and weed biomass (g m\(^{-2}\)) in dry-seeded fine rice sown at 10- and 20-cm row spacing in (a) 2011 and (b) 2012. *** denotes significance at the 0.001 probability level.
density and weed biomass in DSR, even in partial weedy plots. The weed-competitive ability of a particular rice cultivar can be assessed in terms of weed number and biomass under weedy conditions (Zhao et al., 2006). Our data suggest that, under weedy conditions, 10-cm row spacing can provide a significant competitive advantage, thereby limiting the weed burden. Such a reduction in weed growth with narrow crop rows can be attributed to the dense and faster canopy closure that limits light penetration below the leaves (Chauhan and Johnson, 2011), giving the crop a competitive edge. The weed-competitive ability of rice is related to light interception traits. Nevertheless, narrow row spacing can capture most of the intercepted light presumably due to higher leaf area index and greater light interception per unit leaf area, thereby limiting light availability, especially for weeds that need light for germination. Narrow spacing has been suggested to be beneficial to rice farmers, especially in fields where early weed control is implemented (Chauhan and Opeña, 2013a). The use of pre- or early postemergence herbicides can give DSR a weed-free start whereas narrow row spacing can supplement herbicide efficacy through rapid canopy closure later on. In aerobic rice systems, biomass and seed set per plant of *Echinochloa colona* and *Echinochloa crus-galli* were much lower in plots with narrow row spacing than in wider row spacing (Chauhan and Johnson, 2010a). Increased crop competitive ability derived from narrow row spacing, however, needs to be considered in the perspective of integrated weed management (Chauhan, 2012). The use of narrow row spacing in conjunction with efficient herbicide treatments as in the present study supports this hypothesis. Manipulation of cultural practices, such as crop row spacing, can influence and regulate the competitive balance between crops and weeds. Crop row spacing may modify the relative importance of inter- and intraspecific competition by affecting resource acquisition and use. In DSR, when water and nutrients were not limiting as in our study, weed and rice competed mainly for light (Chauhan and Johnson, 2010b) owing to dense canopy characteristics.

The sole herbicide application minimized the damaging effects of weed infestation to a significant extent over the single manual weeding. However, persistence of weeds such as *D. aegyptium*, *E. indica*, *L. chinensis*, and *C. rotundus* was observed even after the sole herbicide application. Previous studies also established that certain weeds still persist in DSR fields after the use of bispyribac-sodium and penoxsulam (Khaliq et al., 2011a, b, 2012a, 2013; Rahman et al., 2012). McDonald and Dernoeden (2006) reported on the selective control of annual grasses by bispyribac-sodium. This necessitates the use of other herbicides, such as fenoxaprop, to tackle leftover weeds, especially grasses.
that are not killed by bispyribac-sodium (e.g., *L. chinensis*, *D. aegyptium*, and *E. indica*). Sequential herbicide application has been found to be superior in DSR to sole application (Khaliq et al., 2011a). Fenoxaprop exhibits phytotoxicity to rice when applied at the early growth stage (before 25 DAS). However, when applied at 30 DAS with a safener, as in our study, it efficiently controlled leftover as well as new flushes of grassy weeds without exhibiting any phytotoxicity to rice. In a previous study, the application of fenoxaprop (100 g ai ha\(^{-1}\) at 30 DAS) also provided excellent control of problematic weeds, such as *Cynodon dactylon* (Gopal et al., 2010). Recently, Chauhan and Opeña (2013b) also reported poor control of *C. rotundus* and *Murdannia nudiflora* (L.) Brenan when either oxadiazon or pendimethalin was followed by a commercial mixture of penoxsulam and cyhalofop. This indicated the herbicide group-based susceptibility, and the urgency to broaden the spectrum of weed control when sedges are dominant. The application of a tank mixture of fenoxaprop + ethoxysulfuron could be beneficial in this regard, and this possibility needs to be explored in future studies (Gopal et al., 2010). Rotation and integration of herbicides with diverse molecular targets can help manage weed peril in DSR, thus simultaneously preventing herbicide selection pressure and shifts in weed populations.

The yield advantage realized with herbicide treatments was pronounced under wider row spacing as plots sown at 10-cm row spacing still had a higher number of panicles and hence grain yield even in partial weedy plots besides weed-free treatments. In a previous study, row spacing ranging from 15 to 45 cm had little effect on rice yields in the absence of weed competition but, under weed competition, wider rows produced significantly lower grain yields (Akobundu and Ahissou, 1985). In contrast, in the present study, yield under narrow row spacing was still higher in weed-free conditions in both years. The reduced weed-crop competition under narrow row spacing may have resulted in more panicles per unit area and subsequently higher yields. Such a difference in rice grain yield in the present study might have originated from the difference in rice cultivar, variable weed species composition and their infestation levels, altered soil moisture regimes, and the prevailing agro-climatic conditions. These results, however, corroborate the previous findings of Chauhan and Johnson (2010a, 2011), who reported higher rice yields under narrow row spacing (15–20 cm) than in wider rows (30 cm). Seedlings growing in close proximity exhibit phytochrome-mediated responses and produce fewer tillers per plant; yet narrow row spacing still resulted in a greater number of panicle-bearing tillers per unit area (Fig. 4). High tillering is not so desirable in DSR (Fageria, 2007) because panicle number (m\(^{-2}\)) depends largely on the main culm rather than tillers (Yoshida, 1981). Moreover, it is advantageous to have more highly productive primary and secondary tillers in DSR than tertiary and quaternary tillers that are less productive and often bear weak panicles. Higher tillering per plant in rice is often associated with increased tiller senescence, fewer spikelets per panicle, smaller panicles, and poor grain filling due to a dilution effect (Peng et al., 1994). However, a dense canopy owing to tiller crowding under narrow row spacing might result in a humid microenvironment conducive to pest or disease attack. Mew (1991) postulated that the incidence of endogenous pathogens, such as *Rhizoctonia solani* Kuhn and *Sclerotium oryzae* Cattaneo, might increase under such conditions. Unfortunately, information regarding the effect of tiller density on pest incidence and crop lodging at maturity remains feeble and this needs to be addressed in future studies (Balasubramanian and Hill, 2002). Nevertheless, no such insect or pathogen attack was noticed in 2011 and 2012 presumably because of effective plant protection measures undertaken during the course of our study.

Herbicide treatments brought about definite yield improvement over the single weeding, but markedly less advantage than the intensive weeding (weed-free plot). This highlights a large scope for closing yield gaps by devising improved weed management tactics in DSR. Moreover, even if weeds surviving after herbicide application do not reduce rice yield, they can still increase the weed seed bank and infestation in subsequent years. Hence, the adoption of an integrated weed management approach seems inevitable under the present scenario (Chauhan, 2012). Weed-free yield (3.23 t ha\(^{-1}\)) in conventional row spacing (20 cm) in the present study was comparable to that achieved by Akbar (2004) under transplanting (3.28 t ha\(^{-1}\)) using the same rice cultivar, when weeds were not a limiting factor in rice production. Interestingly, rice yield under narrow row spacing (10 cm) in our study was much higher than that recorded for conventional transplanted rice under weed-free conditions by Akbar (2004) and Farooq et al. (2008). This may be because of the larger number of panicles per unit area with narrow row spacing (10 cm). Moreover, in manual transplanting, the desired plant population is seldom achieved under farmers’ field conditions and is one of the many limiting factors for higher productivity of transplanted rice cultures.

Rice grain yield in the present study was negatively and linearly associated with weed density and weed biomass. This is not surprising, since weed infestation is much more devastating in rice than in any other upland cereal. Previous studies also revealed a negative correlation between rice yield and weed biomass in DSR (Chauhan et al., 2011). Recently, Khaliq et al. (2013) reported a DSR grain yield loss of 0.75 and 1.06 g m\(^{-2}\) with each unit increase in weed density (m\(^{-2}\)) and biomass (g m\(^{-2}\)), respectively. Unrestricted weed growth can cause a grain
yield penalty of 75 – 90% in DSR (Singh et al., 2008; Chauhan and Johnson, 2011; Khaliq et al., 2013). Therefore, the partial weedy plots in our study were given one manual weeding at 28 DAS. Moreover, in irrigated rice areas, farmers do not allow their rice fields to have uncontrolled weeds. Despite the single weeding in the weedy plots, yields were still 68 – 72% lower than in weed-free plots, suggesting the strong significance of weeds as a limiting factor in DSR production.

The present study demonstrated the effectiveness of narrow row spacing and sequential herbicide application in the wake of efficient weed control in DSR fields. Our findings may promote manufacturers to design seed drills and other intercultural implements that can be used at a narrow row spacing of 10 cm for DSR in Asian countries. Future studies in DSR should focus on the integration and optimization of cultural methods with chemical weed control. Application rate, combinations and the timing of new herbicide molecules need to be explored further under different soil moisture regimes. Moreover, cultivars with greater weed-competitive ability also need to be evaluated under various cultural practices and herbicide combinations. The influence of fertilizer and water inputs on herbicide performance also remains an area of interest.

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