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Effect of crop establishment methods and weed control treatments on weed management, and rice yield

Bhagirath Singh Chauhan[a,*], Tahir Hussain Awan[b], Seth Bernard Abugho[c], Gio Evengelista[b], Sudhir-Yadav[d]

[a] Queensland Alliance for Agriculture and Food Innovation (QAAFI), The University of Queensland, Toowoomba 4350, Queensland, Australia
[b] Crop and Environmental Sciences Division, International Rice Research Institute (IRRI), Los Baños, Philippines
[c] The University of Arkansas, Fayetteville, AR 72704-6898, USA
[d] Crop and Environmental Sciences Division, International Rice Research Institute (IRRI), Hyderabad, India

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ABSTRACT

Lower water availability coupled with labor shortage has resulted in the increasing inability of growers to cultivate puddled transplanted rice (PTR). A field study was conducted in the wet season of 2012 and dry season of 2013 to evaluate the performance of five rice establishment methods and four weed control treatments on weed management, and rice yield. Grass weeds were higher in dry-seeded rice (DSR) as compared to PTR and nonpuddled transplanted rice (NPTR). The highest total weed density (225–256 plants m^{-2}) and total weed biomass (315–501 g m^{-2}) were recorded in DSR while the lowest (102–129 plants m^{-2} and 75–387 g m^{-2}) in PTR. Compared with the weedy plots, the treatment pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D provided excellent weed control. This treatment, however, had a poor performance in NPTR. In both seasons, herbicide efficacy was better in DSR and wet-seeded rice. PTR and DSR produced the maximum rice grain yields. The weed-free plots and herbicide treatments produced 84–614% and 58–504% higher rice grain yield, respectively, than the weedy plots in 2012, and a similar trend was observed in 2013.

1. Introduction

Rice (*Oryza sativa* L.) is consumed as a staple food by more than half of the world's population. In Asia, the major rice production method used is manual transplanting of seedlings into puddled soil. Puddling, a process of cultivating soil in standing water, consumes a large quantity of water (Bouman and Tuong, 2001). However, human population is increasing at an alarming rate and water resources are depleting. Nowadays, water scarcity is a major concern in many regions of the world, as competition between agricultural and industrial consumption of water resources intensifies and climatic unpredictability increases (Hanjar and Quereshi, 2010; Mahajan et al., 2011, 2012). There is a threat that Asian rice growers will probably have inadequate access to irrigation water in the future (Tuong and Bouman, 2003; Mahajan et al., 2013). The scarcity of irrigation water, therefore, threatens the sustainability of rice production in irrigated environments (Chauhan et al., 2012, 2014b). In addition, the migration of rural labor to urban areas, because of industrialization, causes a shortage of labor during the peak season of transplanting in many regions of Asia (Mahajan et al., 2013; Pandey and Velasco, 2005). This results in delays in transplanting, lower grain yield, and delays in planting of the next crop. Puddling also has deteriorating effects on soil structure, which adversely affect the subsequent nonrice crop (Timsina and Connor, 2001).

Several studies in China (Yan et al., 2010), South Asia (Gupta et al., 2002; Malik and Yadav, 2008), and Australia (Beecher et al., 2006) have revealed that rice can be successfully grown using dry seeding. Dry-seeded rice (DSR) has been developed as an alternative method of rice establishment that reduces labor requirements and other inputs while increasing or maintaining economic productivity and alleviating soil degradation problems (Ladha et al., 2009; Farooq et al., 2011). However, some studies reported a reduction in yield when shifting from puddled transplanted rice (PTR) to DSR using alternate wetting and drying (AWD) water management (Bhushan et al., 2007; Choudhury et al., 2007). The yield reductions were related to the management practices applied and the climatic conditions in the planting site (Belder et al., 2004; Gathala et al., 2006; Kato et al., 2009; Singh et al., 2011).

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[*] Corresponding author. Tel.: +61 07 4639 8838.
E-mail address: b.chauhan@uq.edu.au (B.S. Chauhan).

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DSR can be sown after conventional tillage or under zero-till conditions (Chauhan and Opeña, 2012). Zero-till systems require less labor and fuel compared with conventional tillage systems (Chauhan and Johnson, 2009). The sustainability of DSR, however, is endangered by heavy weed infestations (Chauhan, 2012; Mahajan et al., 2013). Weed control is particularly challenging in DSR systems because of the diversity and severity of weed infestation, the absence of standing water layer to suppress weeds at the time of rice emergence, and no seedling size advantage of rice over the weed seedlings as both emerge simultaneously. In DSR systems, land preparation operations influence weed seed distribution in the soil profile and the comparative abundance of weed species (Chauhan and Opeña, 2012).

The shifts in weed flora composition in agricultural cropping systems have been widely documented. These changes resulted from selection pressures imposed by modifications and innovations in agricultural technologies, which have altered weed habitats to some extent (Haas and Streibig, 1982; Hall et al., 2000). Differences in weed flora also depend on the rice establishment method used. A large number of perennial species [*Paspalum distichum* L., *Cynodon dactylon* (L.) Pers., *Cyperus rotundus* L.] as well as annual grasses (*Ischaemum rugosum* Salisb.) and annual sedges [*Cyperus difformis* L. and *Fimbristylis miliacea* (L.) Vahl] were found in conventional-till DSR systems (Timsina et al., 2010). In the same study, less growth of perennial weeds (*C. dactylon, P. distichum*, and *C. rotundus*) and annual weeds (*I. rugosum* and *F. miliacea*) was observed in the zero-till DSR system compared with the conventional-till DSR system. In another study in DSR, *Echinochloa crus-galli* (L.) P. Beauv. appeared after three successive seasons, followed by *Leptochloa chinensis* (L.) Nees (after 10 consecutive seasons), *I. rugosum* (after 14 consecutive seasons), and weedy rice (after 20 consecutive seasons) (Ho, 1996).

In Asia, hand weeding and herbicides are used to control weeds, but manual weeding is becoming less common because of labor scarcity and its high cost. The use of herbicides in rice has increased because it saves labor and is less costly, and the herbicides are easy to apply. The use of a single herbicide, however, does not provide effective weed control in DSR because of the complex mixture of weed species (Chauhan, 2012). Previous research showed that cultural practices such as seeding method, land cultivation, and water and fertilizer management affected weed flora and weed infestations in DSR (Moody, 1993; Bhagat et al., 1999; Tuong et al., 2000; Phuong et al., 2005).

There are some aspects of alternative rice establishment technologies that are not yet well-understood, especially in relation to studies addressing a systematic comparison of weed infestation, weed control efficiency, and rice yield in transplanted rice (puddled and nonpuddled), WSR (puddled and nonpuddled), and DSR. We hypothesized that modifications and innovations of agricultural technologies, such as land preparation operations, establishment methods, and weed control methods, have different effects on weed flora composition and rice productivity. Therefore, a study was conducted at the farm of the International Rice Research Institute to evaluate the effect of different rice establishment methods and weed control treatments on weed emergence, weed growth, and rice yield.

2. Material and methods

2.1. Experimental site

Experiments were conducted at a farm at the International Rice Research Institute (IRRI), Los Baños (14′13°N, 121′13°E, 23 m above sea level), Philippines, during the wet season (WS) of 2012 and the dry season (DS) of 2013. The soil at the site was clay loam with 0.9% organic carbon and 6.1 pH (Sudhir-Yadav Evangelista et al., 2014).

2.2. Experimental design

The experiment was laid out in a split-plot design with three replications. Five rice establishment methods in the main plots and four weed control treatments in the subplots were evaluated in both seasons. The rice establishment methods involved a combination of tillage treatments (puddled or dry tilled) and planting methods (transplanting or direct seeding) as follows: (1) PTR (20 × 20 cm), (2) nonpuddled transplanted rice (NPTR) (20 × 20 cm), (3) surface-seeded rice on puddled soil using a drum seeder (wet-seeded rice, WSR), (4) surface-seeded rice on nonpuddled soil using a drum seeder (nonpuddled wet-seeded rice, NWSR), and (5) DSR in dry cultivated soil. The four weed control treatments were (1) pretilachlor (600 g a.i. ha^{-1} in DSR and 300 g a.i. ha^{-1} in other establishment methods) applied at two days after sowing (DAS) in DSR and two days after transplanting (DAT) in transplanted rice followed by fenoxaprop plus ethoxysulfuron (0.045 kg a.i. ha^{-1}) tank mixed with 2,4-D (0.5 kg a.i. ha^{-1}) at 21 DAS/DAT, (2) pretilachlor (600 g a.i. ha^{-1} in DSR and 300 g a.i. ha^{-1} in other establishment methods) followed by fenoxaprop plus ethoxysulfuron (0.045 kg a.i. ha^{-1}) at 21 DAS/DAT, (3) weedy, and (4) weed-free. In the weedy plots, weeds were not removed. However, weed inflorescences were removed to avoid addition of weed seeds in the seed bank. In the weed-free plots, weeds were controlled using weed control treatment (1) plus hand weedings, whenever needed.

2.3. Crop management

Prior to the 2012 WS experiment, the land was dry cultivated using a twin-axle tractor with discings followed by two passes of a tractor-mounted rotavator. For the puddled treatments, the soil was irrigated three days before puddling (three passes) using a power tiller. The test variety used in this study was NSIC Rc222 (IR154), a short duration (110 d) variety. DSR was sown on 17 May 2012 (2012 WS) and 2 December 2012 (2013 DS). The rice seeds were sown at 45 kg ha^{-1} with a 4-wheel tractor-drawn seed drill at a row spacing of 20 cm and depths of 1–2 cm. For all establishment methods except DSR, the seeds were soaked in water for 24 h. The seeds were then incubated for 8-10 hours prior to sowing by a drum-seeder on puddled (WSR) and nonpuddled soil (NWSR), and on the seedbed for raising nursery for the transplanted treatments. The 17-day-old seedlings were transplanted at 20 cm × 20 cm geometry on well-puddled soil.

All treatments received a basal fertilizer application (30 kg P ha^{-1} as single super phosphate, 30 kg K ha^{-1} as muriate of potash, and 15 kg Zn ha^{-1} as zinc sulphate) prior to the last cultivation/puddling. Nitrogen in the form of urea was applied at 200 kg ha^{-1} in four splits at 15, 31, 45, and 60 DAS/DAT. Urea was applied on the soil when there was no standing water. Immediately after broadcasting of urea, irrigation was applied. The herbicides were applied with a knapsack sprayer having a delivery of about 320 L ha^{-1} of spray solution through a flat fan nozzle at a spray pressure of 140 kPa.

The soil was kept near saturation from sowing to 21 DAS in the direct-seeded plots, while it was kept under flooded conditions (2–3 cm) from transplanting to 8 DAT in the transplanted plots. The plots were then kept under AWD conditions and irrigation was applied when soil water tension had increased to 10 kPa at 15 cm soil depth, at an average of three replications.

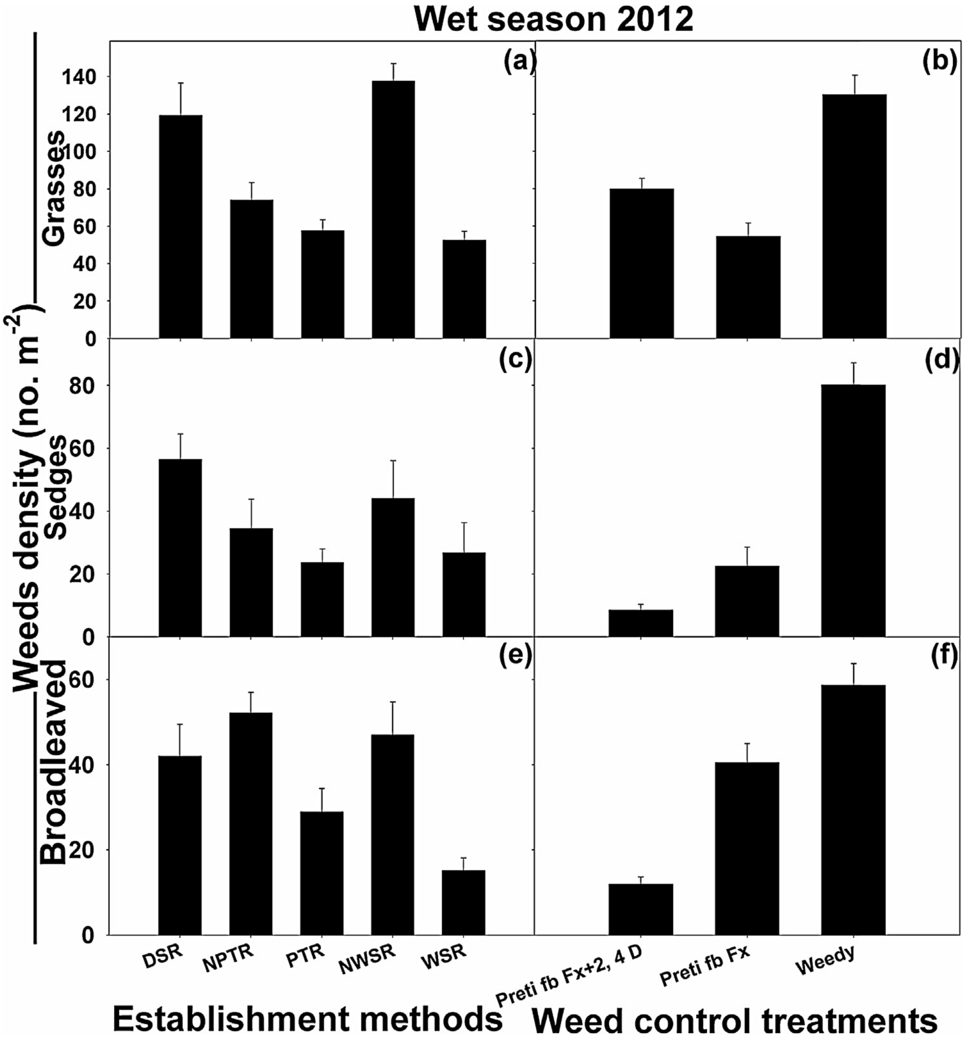

Fig. 1. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed density at 14 days after sowing/transplanting in the wet season of 2012.

2.4. Measurements and observations

Herbicide efficacy was evaluated at 14 DAS/DAT (after the application of preemergence but before the spray of postemergence herbicides) and at flowering (after the application of all weed control treatments). At each sampling time, two quadrats of 40 cm × 40 cm were placed randomly in each plot to determine the density and biomass of weeds. Weeds were uprooted manually and brought to a screenhouse. These were identified, counted into three groups (grasses, sedges, and broadleaved), separately oven dried at 70 °C for constant dry weight, and measured for biomass. At maturity, the rice crop was harvested from an area of 4.8 m^2. After threshing and cleaning, the weight and moisture percentage of grains were recorded. Grain yield was converted to $kg\,ha^{-1}$ at 14% moisture content.

2.5. Statistical analyses

Data were analyzed using analysis of variance (ANOVA) to evaluate the differences among treatments while the means were separated using the least significant difference (LSD) test at the 5% level of significance. Weed density and biomass data were subjected to transformation; however, it did not improve the homogeneity of variance. Therefore, original values were used in ANOVA (GenStat 8.0, 2005). The relationship between grain yield ($kg\,ha^{-1}$) and weed biomass ($g\,m^{-2}$) at flowering was assessed using linear regression analysis (SigmaPlot 10.0).

3. Results

3.1. Grass, sedge, and broadleaved weed density at 14 DAS/DAT and flowering

The analysis of data showed significant differences among the rice establishment methods for the grass weed density ($p = 0.002$) at 14 DAS/DAT in 2012 (Fig. 1) and for the weed density of broadleaved weeds at 14 DAS/DAT ($p = 0.001$) in 2013 (Fig. 2) and at flowering ($p = 0.002$) in 2013 (Fig. 2). At 14 DAS/DAT, the maximum grass density was recorded in NWSR and NPTR in 2012 and 2013, respectively (Figs. 1 and 2), whereas at flowering, it was found in DSR and NPTR in 2012 and 2013, respectively (Figs. 3 and 4). At 14 DAS/DAT, the sedge density was maximum in DSR and in PTR in 2012 and 2013, respectively, while at flowering, both the sedge and broadleaved densities were maximum in NWSR and NPTR in both years (Figs. 3 and 4).

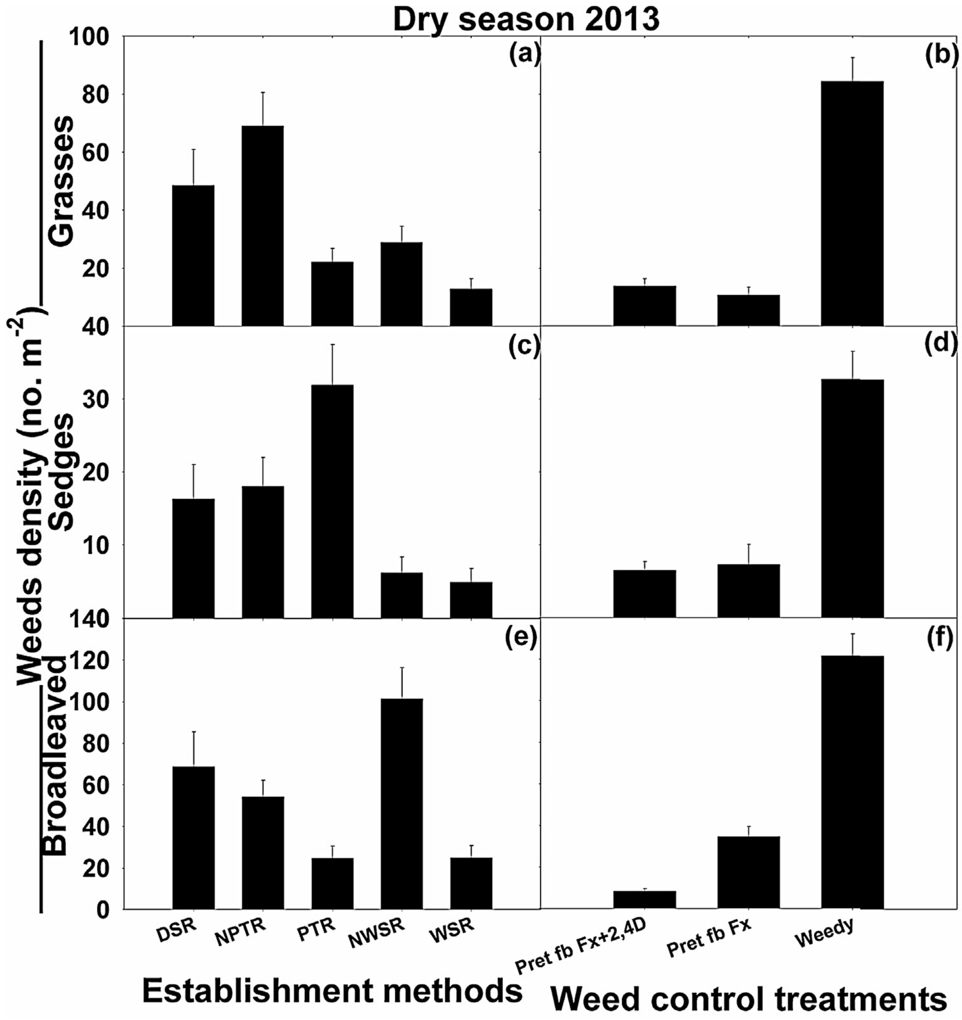

Fig. 2. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed density at 14 days after sowing/transplanting after sowing in dry season of 2013.

Weed control treatments significantly affected grass, sedge, and broadleaved weed densities at 14 DAS/DAT and at flowering in both years, except the sedge density ($p = 0.28$) at flowering in 2012. A similar trend was observed in 2013 (Figs. 2 and 4). The maximum grass, sedge, and broadleaved weed densities were recorded in the weedy check plots while the application of herbicides reduced the density of all the three weed groups in both years. Among the herbicide treatments, both pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D and pretilachlor followed by fenoxaprop plus ethoxysulfuron provided similar control of grasses and sedges, but the addition of 2,4-D provided good control of broadleaved weeds during both years (Figs. 1–4).

3.2. Grass, sedge, and broadleaved weed biomass at 14 DAS/DAT and at flowering

Interaction between the rice establishment methods and the weed control treatments was nonsignificant for most of the biomass of individual weeds in either year of the study. However, highly significant differences were noted among the weed control practices during both years, while the rice establishment methods affected the weed biomass of broadleaved ($p = 0.022$) and sedge ($p = 0.001$) at 14 DAS/DAT in 2012 (Fig. 5), and broadleaved weeds at 14 DAS/DAT ($p = 0.001$) in 2013 (Fig. 6) and at flowering ($p = 0.025$) in 2013 (Fig. 8).

The effects of different rice establishment methods on grass biomass were nonsignificant at 14 DAS/DAT and at flowering in the 2012 WS (Figs. 5 and 7), while the effects were significant only at flowering in the 2013 DS (Fig. 8). In 2012, the highest grass weed biomass was recorded in NPTR and NWSR (94 and 95 g m^{-2} at 14 DAS/DAT, respectively, and 94 and 205 g m^{-2} at flowering, respectively) (Figs. 5 and 7). A similar trend was observed in 2013 (Figs. 6 and 8). In 2012, the highest sedge biomass was recorded in NWSR (12.6 g m^{-2}) at 14 DAS (Fig. 5) and in PTR (8.3 g m^{-2}) at flowering (Fig. 7) as compared to the other establishment methods. In 2013, the highest sedge biomass was recorded in PTR (5.6 g m^{-2}) at 14 DAT (Fig. 6) and in NPTR (9.7 g m^{-2}) and PTR (5.6 g m^{-2}) at flowering (Fig. 8). In both seasons, the lowest sedge biomass was recorded in WSR at 14 DAS and in DSR and WSR at flowering. In the 2012 WS, the highest broadleaved weed biomass was recorded in NPTR (8.39 g m^{-2}) and NWSR (6.2 g m^{-2}) at 14 DAS/DAT (Fig. 5) and in WSR (12.9–16.3 g m^{-2}) at flowering (Fig. 7). In the 2013 DS, the highest broadleaved weed biomass was recorded in NWSR (18.9 g m^{-2}) at 14 DAS/DAT (Fig. 6) and also at flowering (46.7 g m^{-2}) (Fig. 8).

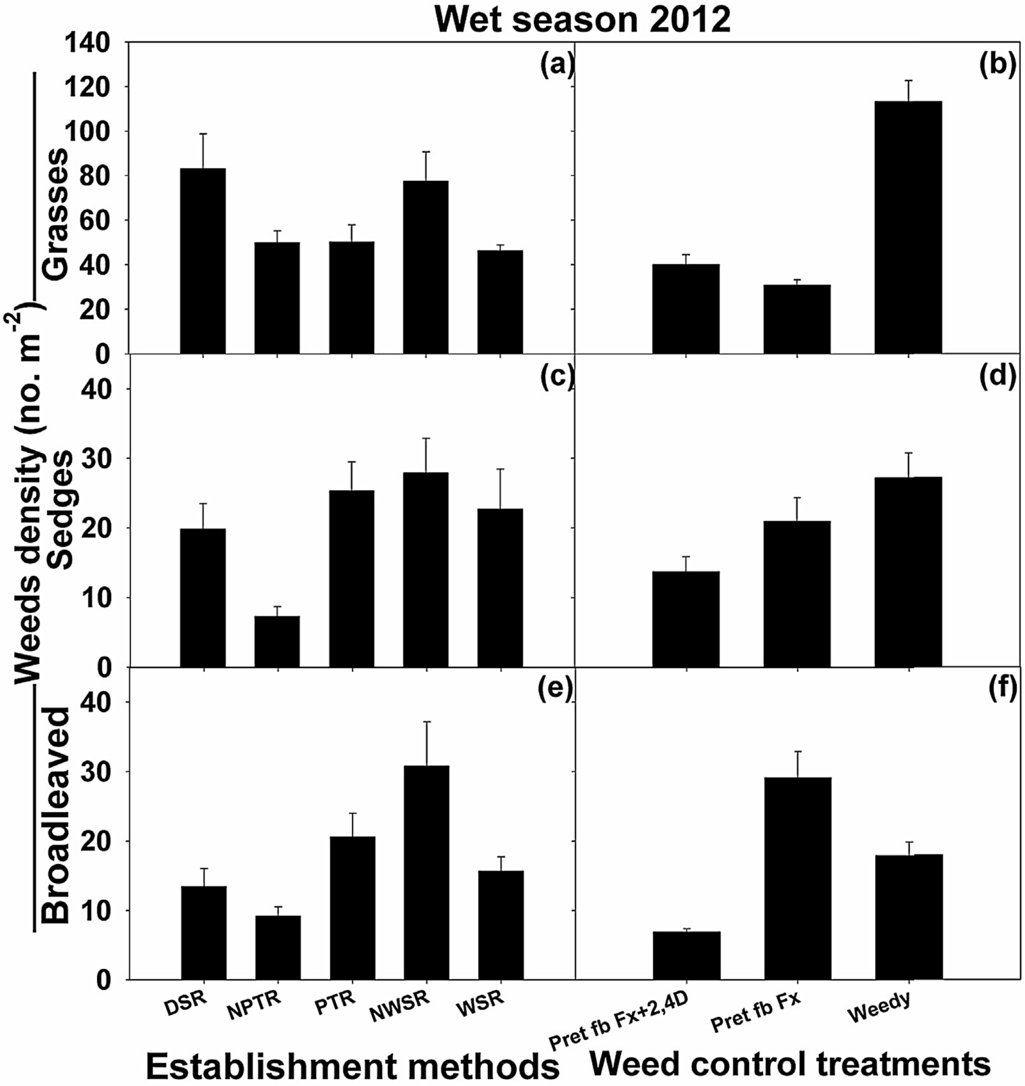

Fig. 3. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed density at flowering in the wet season of 2012.

3.3. Total weed density at 14 DAS/DAT

ANOVA showed significant interaction between planting techniques and weed management practices in both seasons in terms of total weed density at 14 DAS/DAT (Table 1). However, the interaction was predominantly due to the large differences in the number of weed seedlings among the different establishment methods in the weedy plots. At 14 DAS in the 2012 WS, the maximum weed density was recorded in NWSR (229 plants m^{-2}) and in DSR (218 plants m^{-2}), while the minimum weed density was recorded in WSR (94 plants m^{-2}) (Table 1). In the 2013 DS, the maximum weed density was noted in NPTR (141 plants m^{-2}) followed by NWSR with 137 plants m^{-2} and DSR with 134 plants m^{-2}. On the other hand, the lowest weed density was recorded in WSR at 43 plants m^{-2}, similar to that of the data observed for 2012.

Total weed density was highest in the weedy plots (193–402 plants m^{-2}) than in the other weed control treatments in all the establishment methods. In the 2012 WS, the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D had a weed density of 41–151 plants m^{-2}, which was similar to the weed density in the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron (46–191 plants m^{-2}) in all the establishment methods. The lowest weed density among the weed control treatments was recorded in WSR (41, 46, and 196 plants m^{-2}) and PTR (66, 71, and 193 plants m^{-2}) in the treatments of pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D, pretilachlor followed by fenoxaprop plus ethoxysulfuron, and weedy check, respectively. In the 2013 DS, the lowest weed density was recorded in WSR (6 and 10 plants m^{-2}) and DSR (22 and 5 plants m^{-2}) in the weed control treatments of pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D, and pretilachlor followed by fenoxaprop plus ethoxysulfuron, respectively.

3.4. Total weed biomass at 14 DAS/DAT

Interaction between planting methods and weed control treatments was nonsignificant during both years. However, highly significant differences for weed biomass were noted among the weed control treatments in both years, while the establishment techniques affected total weed biomass only in 2013 (Table 1). In 2012, across the weed control treatments, the plots under PTR,

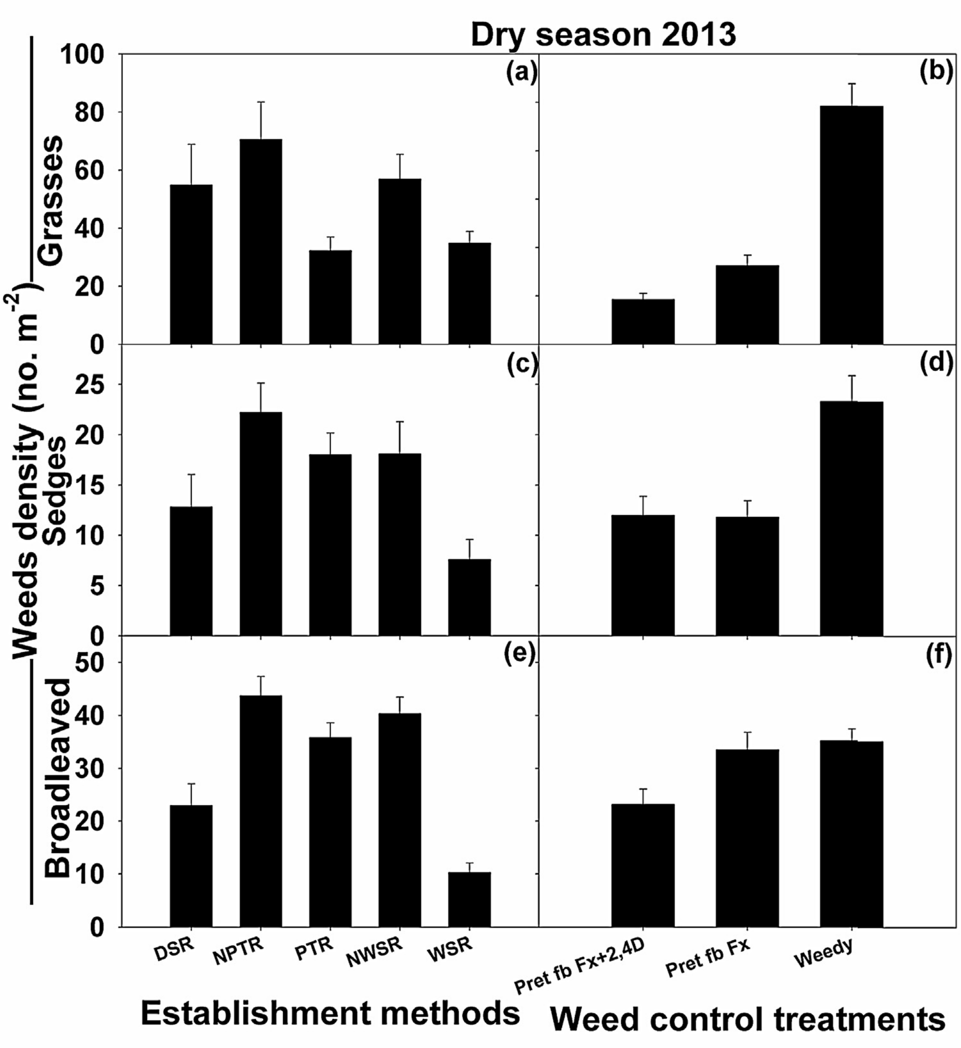

Fig. 4. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed density at flowering in the dry season 2013.

WSR, and DSR had lower weed biomass (63, 75, and 86 g m^{-2}, respectively) than the NPTR (105 g m^{-2}) and NWSR (114 g m^{-2}) plots (Table 1). A similar trend was observed in 2013, in which transplanting after puddling (PTR) (13.4 g m^{-2}), drum seeding after puddling (WSR) (8.10 g m^{-2}), and DSR (31.3 g m^{-2}) resulted in lower weed biomass as compared to the other establishment methods (36–37 g m^{-2}). For the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D and pretilachlor followed by fenoxaprop plus ethoxysulfuron, lower weed biomass was recorded in WSR (0.3 and 0.7 g m^{-2}, respectively) and DSR (2.6 and 0.3 g m^{-2}, respectively) as compared to the other establishment methods.

In both years, across the planting methods, the average maximum weed biomass was recorded in the weedy check plots (206 and 63 g m^{-2} in 2012 and 2013, respectively) as compared to the average weed biomass obtained in the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D (28 and 5 g m^{-2}) and pretilachlor followed by fenoxaprop plus ethoxysulfuron (32 and 8 g m^{-2}). The results of both herbicide treatments were similar at 14 DAS/DAT because only pretilachlor (as preemergence) was applied at this stage and no postemergence herbicide was applied yet.

3.5. *Total weed density at flowering*

Total weed densities in the weedy plots were 193–402 plants m^{-2} in 2012 and 111–374 plants m^{-2} in 2013 at 14 DAS/DAT (Table 2). However, these values significantly reduced at flowering to 91–256 plants m^{-2} and 101–225 plants m^{-2} in 2012 and 2013, respectively, in all the establishment methods (Table 2). In 2012, the highest weed density in the weedy plots was recorded in DSR (256 plants m^{-2}) while the lowest weed density was observed in transplanted rice (91–102 plants m^{-2}). In 2013, the highest weed density was also recorded in DSR (225 plants m^{-2}) but the lowest was recorded in WSR (101 plants m^{-2}) (Table 2).

In DSR, compared with the weedy plots, the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D had 83 and 89% lower total weed density in the wet and dry seasons, respectively, whereas in the other establishment methods, these values were only 15–66% and 42–80%, respectively. Pretilachlor followed by fenoxaprop plus ethoxysulfuron also performed very effectively in DSR, reducing the density by 80 and 90% in the wet and dry seasons, respectively, compared with the weedy plots. A poor performance of these herbicides was observed in NPTR, in

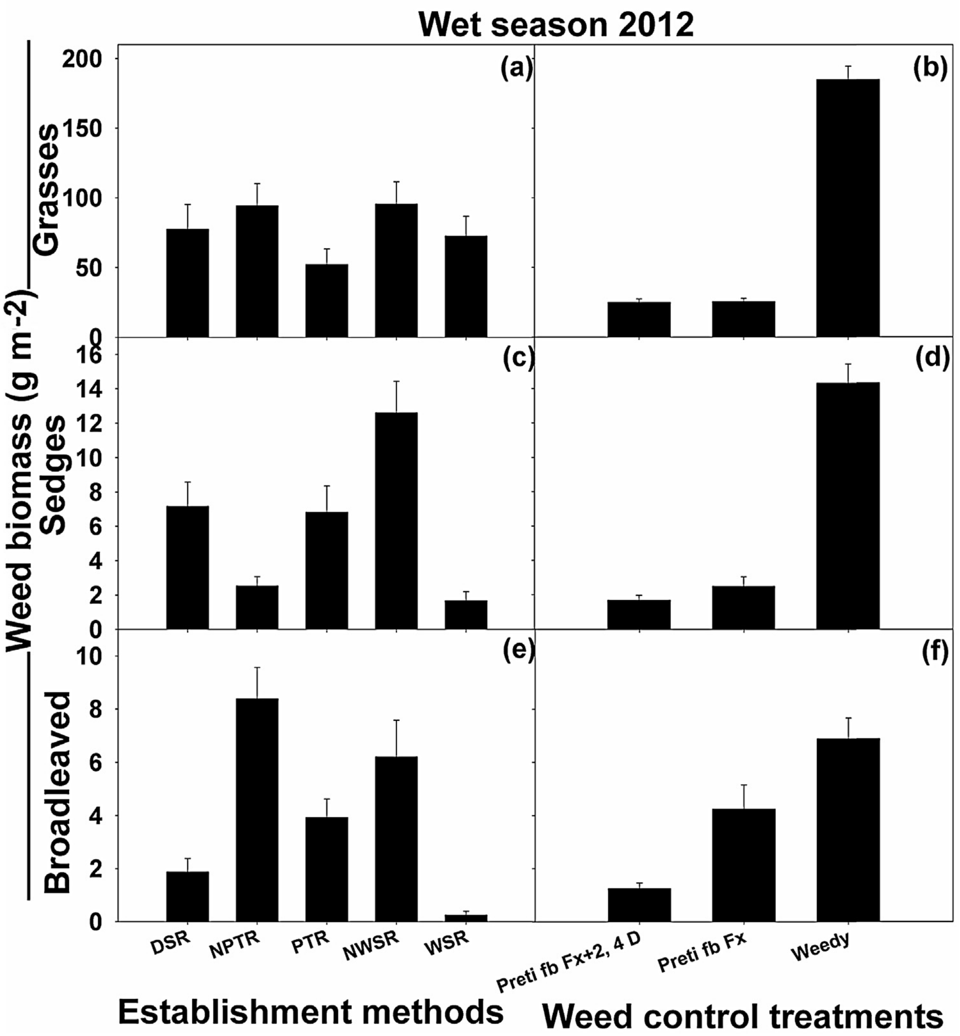

Fig. 5. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed biomass at 14 days after sowing/transplanting in the wet season of 2012.

which they reduced the density by only 15 and 2% in 2012, and 58 and 42% in 2013, respectively (Table 2).

In the weedy plots, the maximum weed density was recorded in DSR during both years (256 plants m^{-2} in 2012 and 225 plants m^{-2} in 2013) while the minimum density was recorded in NPTR (91 plants m^{-2}) in 2012 and WSR (101 plants m^{-2}) in 2013. In both years, herbicide efficacy was better in DSR and WSR. On the other hand, herbicide efficacy was poor in NWSR in 2012 and in NWSR and NPTR in 2013. Among the rice establishment methods, PTR, DSR, and WSR resulted in lower weed biomass as compared to NPTR and NWSR. Among the weed control methods, the maximum weed density was recorded in the weedy check plots.

3.6. *Total weed biomass at flowering*

Total weed biomass under different planting methods and weed control treatments was higher at flowering than at 14 DAS/DAT. Across the weed control methods, the highest weed biomass was recorded in NWSR (221 g m^{-2}), followed by NPTR (198 g m^{-2}) (Table 2). Herbicide treatments had a significant effect in reducing weed biomass in all the planting methods. The lowest weed biomass was recorded in PTR (155 g m^{-2}). In 2012, the highest weed biomass was recorded in the weedy plots (at an average of 483 g m^{-2}), which reduced by 94% in the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D and 89% in the pretilachlor followed by fenoxaprop plus ethoxysulfuron treatment. Without weed control, the maximum weed biomass was produced in NWSR (583 g m^{-2}) while the minimum was produced in PTR (387 g m^{-2}). A similar trend was observed in the 2013 DS, with the maximum weed biomass produced in NWSR (332 g m^{-2}) and the minimum in WSR (75 g m^{-2}). Across the planting methods, herbicide treatments recorded similar weed biomass in 2012. The application of pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D reduced weed biomass by 92–95% and pretilachlor followed by fenoxaprop plus ethoxysulfuron reduced weed biomass by 82–93%, compared with the weedy plots. In 2013, the performance of the weed control treatments was affected by establishment methods. The efficacy of both herbicide treatments (i.e., pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D and pretilachlor followed by fenoxaprop plus ethoxysulfuron) was better in DSR than in the other establishment methods and these treatments reduced weed biomass by 95 and 94%, respectively, compared with the weedy plots. Poor efficacy of these treatments was recorded in NPTR, in which they reduced weed biomass by only 62 and 58%, respectively, as compared to the weedy plots. In both seasons, irrespective of the planting method, the

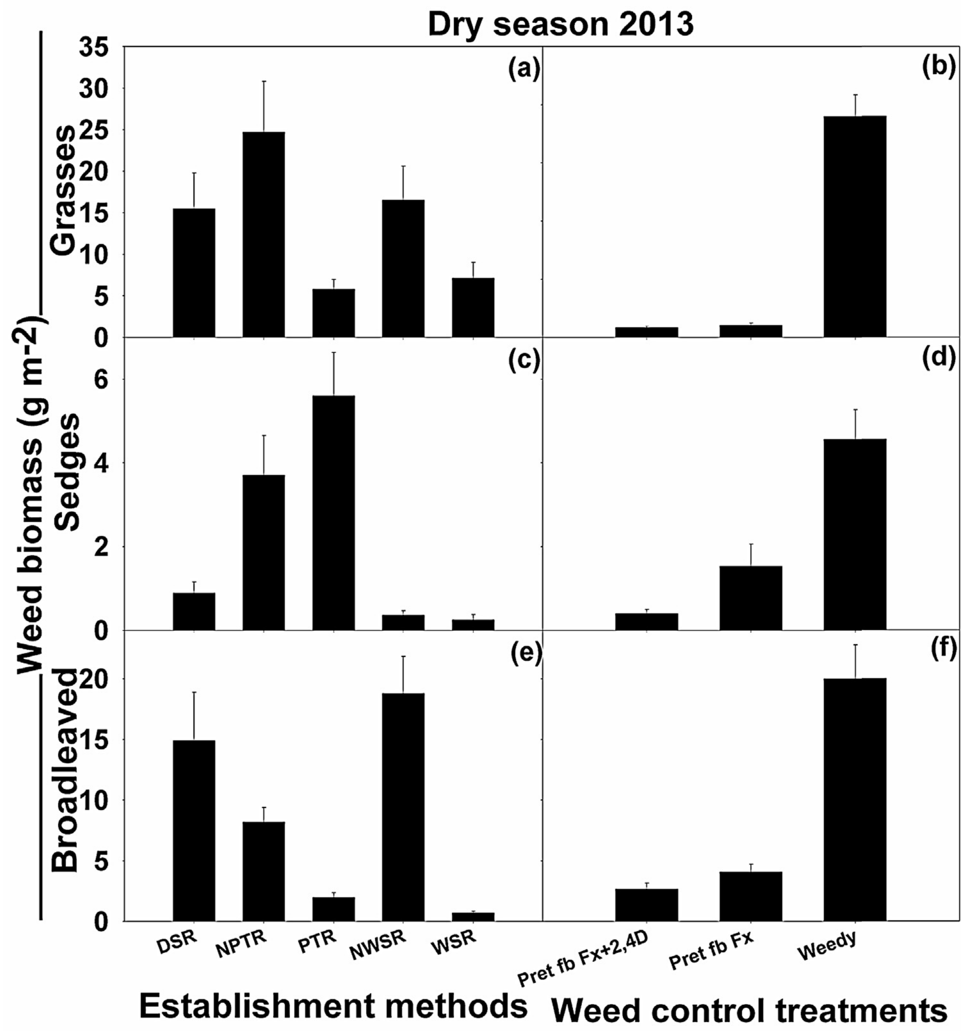

Fig. 6. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed biomass at 14 days after sowing/transplanting in the dry season of 2013.

application of pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D produced lower weed biomass as compared to pretilachlor followed by fenoxaprop plus ethoxysulfuron.

In the best weed control treatment (i.e., pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D), both DSR and WSR plots exhibited lower total weed densities (42 and 23 plants m^{-2} in 2012 and 2013, respectively, for DSR, and 49 and 20 plants m^{-2} in 2012 and 2013, respectively, for WSR) and total weed biomass (23 and 15 g m^{-2} in 2012 and 2013, respectively, for DSR, and 29 and 13 g m^{-2} in 2012 and 2013, respectively, for WSR) as compared to the other rice establishment methods (Table 2).

3.7. Relationships between weed density, weed biomass, and rice grain yield.

In both years, a negative linear correlation was found between weed density and grain yield (data not shown), and weed biomass and grain yield (Fig. 9). Weed biomass had a stronger relationship with grain yield than weed density. The relationship was slightly stronger in the 2012 WS ($R^2 = 0.78$) than in the 2013 DS ($R^2 = 0.69$) (Fig. 9). Regression analysis showed that 100 g weed biomass m^{-2} at flowering reduced rice grain yield by 650 kg ha^{-1} in the 2012 WS and 1150 kg ha^{-1} in the 2013 DS.

3.8. Rice grain yield

Establishment methods and weed control treatments affected ($p < 0.001$) rice grain yield in both seasons. However, the interactions of the rice planting methods and weed control treatments were nonsignificant during both seasons. In 2012 and 2013, respectively, the maximum grain yield was recorded in PTR (3323 and 5689 kg ha^{-1}) and in NPTR (3352 and 6401 kg ha^{-1}), followed by DSR (2642 and 5339 kg ha^{-1}) (Fig. 10). On the other hand, the lowest rice grain yield was recorded in NWSR (1509 and 4519 kg ha^{-1} in 2012 and 2013, respectively).

Compared with the weedy plots, the other weed control treatments produced higher ($p < 0.001$) rice grain yield. In 2012, relative to the weedy check, the weed-free treatment produced 614% (3903 kg ha^{-1}) higher yield, which was followed by the treatment pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D (504% higher) and then, the treatment pretilachlor followed by fenoxaprop plus ethoxysulfuron (479% higher). A similar trend was observed in 2013 (Fig. 10). Weeds in the weedy check plots reduced rice grain yield by 86% and 46% in 2012 and 2013, respectively,

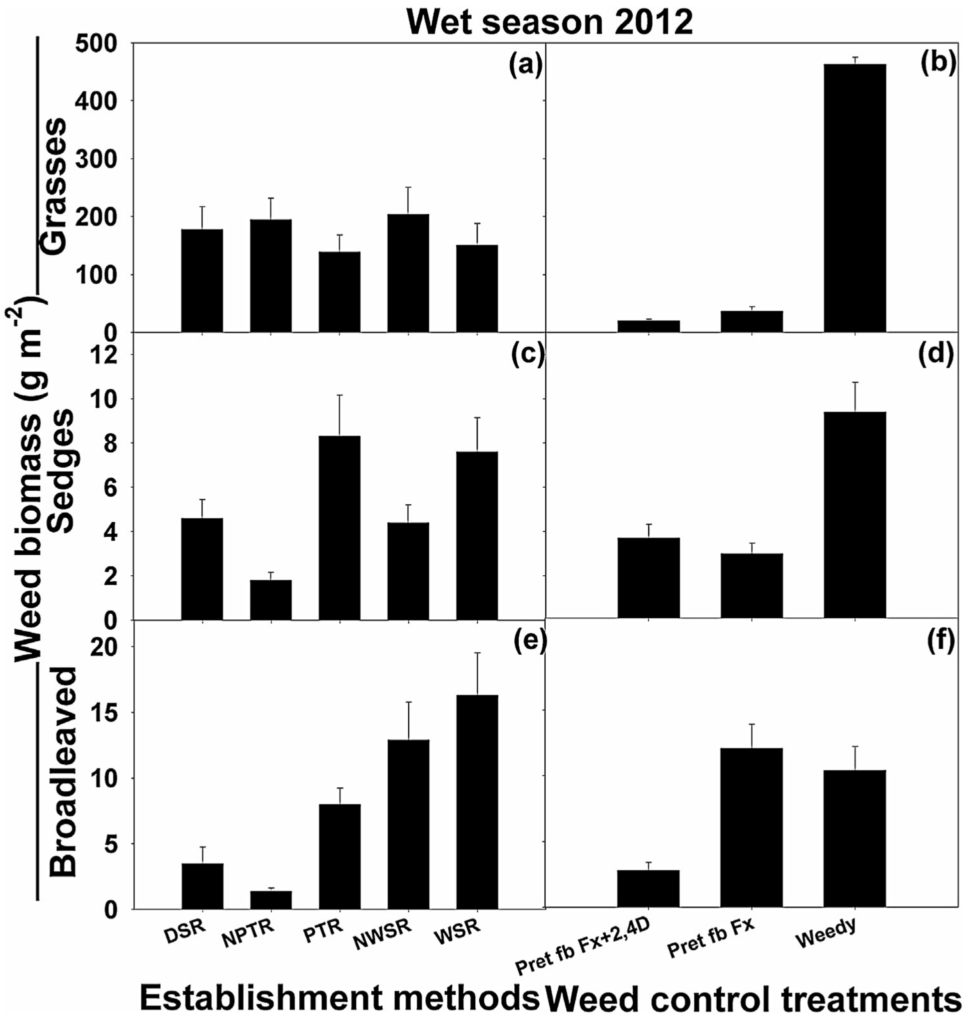

Fig. 7. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed biomass at flowering in the wet season of 2012.

compared to the weed-free check. Compared with the weed-free plots, the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D and pretilachlor followed by fenoxaprop plus ethoxysulfuron produced 19 and 15% less rice grain yield in 2012 and 15 and 7% less rice grain yield in 2013, respectively.

4. Discussion

Our results showed that grasses were the dominant weeds in the plots sown in NWSR and NPTR, while sedges were dominant in transplanted and wet-seeded rice, and broadleaved weeds had higher density and biomass in wet-seeded rice. These results of different weed groups being dominant in different rice establishment methods were similar to the findings of a study conducted in Bangladesh, in which land preparation methods for conventional-till DSR did not prove effective in limiting perennial weed growth (Timsina et al., 2010). The conventional-till DSR had higher grass (108 plants m^{-2}) and sedge (180 plants m^{-2}) densities while PTR had only 9 and 98 plants m^{-2} of grass and sedge densities, respectively. Fewer weeds occurred in PTR than in DSR, which may be because the repeated puddling made in PTR provided good control of weeds. In another study in Sri Lanka, transplanted rice method was the most effective in reducing weedy rice panicles and seed production, and produced the highest rice grain yield (Chauhan et al., 2014a). In transplanted rice, there is an advantage of seedling size. These rice seedlings are more competitive against the emerging weed seedlings. There is also standing water in the field at the time of transplanting and standing water is known to suppress the emergence of several weeds (Chauhan and Johnson, 2010). In the weedy plots, at 14 DAS/DAT, the maximum weed density was recorded in DSR as compared to the other rice establishment methods. However, averaged over the weed control methods, the maximum weed density was recorded in drum seeding after dry tillage (NWSR) and transplanting after puddling (PTR), while the minimum weed density was recorded in DSR. The main reason for this is that the herbicides were very effective in DSR, reducing weed density more in DSR than in the other planting methods, which ultimately lowered the average weed density. In a study in Bangladesh, weed densities were higher in the conventional-till DSR than in transplanted rice and a substantially higher weed biomass was noted in the conventional-till DSR than in PTR for any given weed control method (i.e., weedy, two hand weedings, and one herbicide application plus one hand weeding, respectively) (Timsina et al., 2010). In the same study, without any weed control, higher weed growth was recorded in the conventional-till DSR.

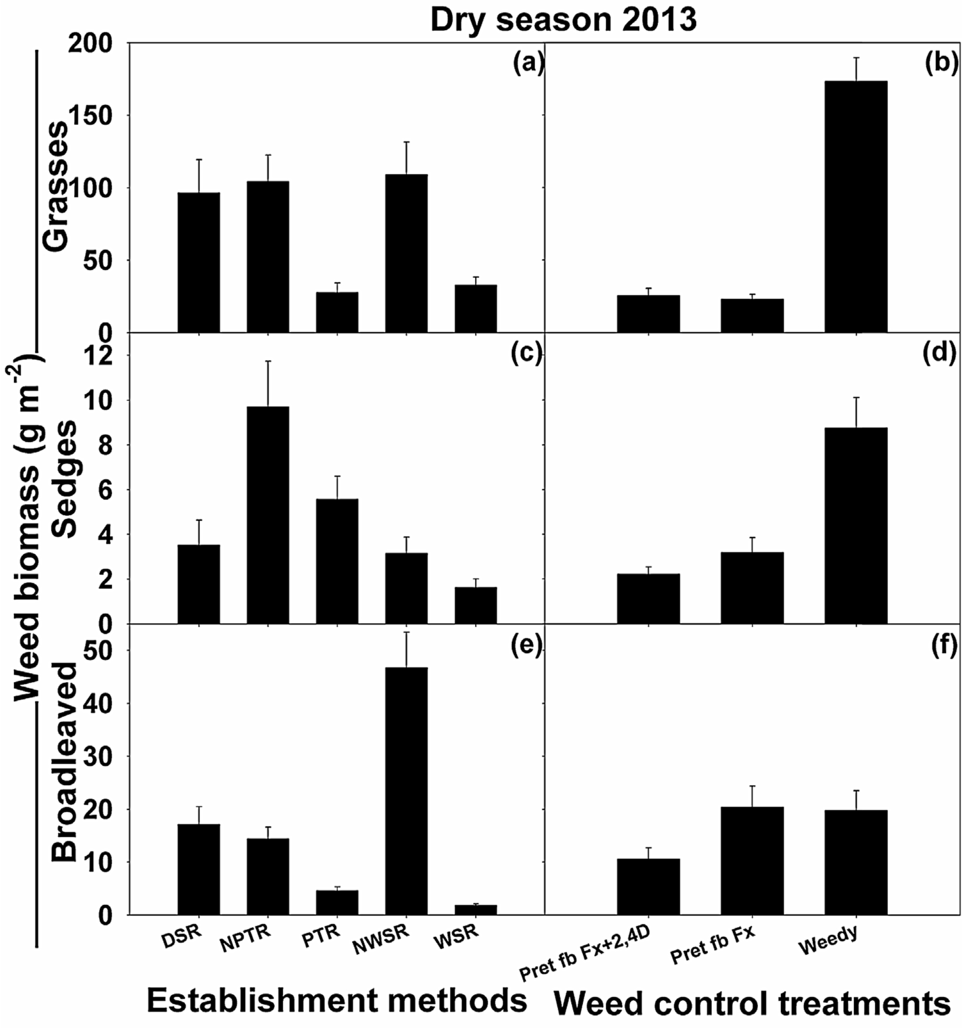

Fig. 8. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on grass (a, b), sedge (c, d), and broadleaved (e, f) weed biomass at flowering in the dry season of 2013.

Table 1

Effect of rice establishment methods (DSR, dry drill-seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4-D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on total weed density and biomass at 14 days after sowing/transplanting in the wet season of 2012 and dry season of 2013.

Rice establishment method	Wet season 2012			Dry season 2013		
	Total weed density (no. m^{-2})			Total weed density (no. m^{-2})		
	Preti fb Fx + 2, 4 D	Preti fb Fx	Weedy	Pre fb Fx + 2,4D	Pret fb Fx	Weedy
DSR	122.0	129.0	402.0	22.0	5.0	374.0
NPTR	121.0	151.0	209.0	52.0	99.0	273.0
PTR	66.0	71.0	193.0	26.0	70.0	141.0
NWSR	151.0	191.0	344.0	36.0	79.0	295.0
WSR	41.0	46.0	196.0	6.0	10.0	111.0
LSD$_{0.05}$		126.5			116.1	

Rice establishment method	Wet season 2012			Dry season 2013		
	Total weed biomass (g m^{-2})			Total weed biomass (g m^{-2})		
	Preti fb Fx + 2, 4 D	Preti fb Fx	Weedy	Pre fb Fx + 2,4-D	Pret fb Fx	Weedy
DSR	19.2	23.1	217.0	2.6	0.3	91.0
NPTR	52.2	58.7	205.0	9.8	16.7	83.3
PTR	13.6	12.1	163.0	3.7	11.0	25.6
NWSR	38.9	45.8	259.0	7.4	10.0	89.5
WSR	15.4	21.7	186.0	0.3	0.7	23.3
LSD$_{0.05}$		87.6			30.3	

Table 2
Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, Wet drum seeding on puddled soil) and weed control treatments (Preti fb Fx plus 2,4-D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) on total weed density and biomass at flowering in the wet season of 2012 and dry season of 2013.

	Wet season 2012			Dry season 2013		
	Total weed density (no. m^{-2})			Total weed density (no. m^{-2})		
	Preti fb Fx + 2, 4 D	Preti fb Fx	Weedy	Pre fb Fx + 2,4D	Pret fb Fx	Weedy
DSR	41.6	51.0	256.2	23.7	22.9	225.0
NPTR	52.1	56.2	90.6	78.1	161.5	169.8
PTR	86.4	100.0	102.1	54.2	74.5	129.2
NWSR	73.1	138.8	196.6	92.7	92.7	160.4
WSR	49.6	58.4	145.9	19.8	25.6	101.0
LSD$_{0.05}$		100.0			107.7	

Rice establishment method	Wet season 2012			Dry season 2013		
	Total weed biomass (g m^{-2})			Total weed biomass (g m^{-2})		
	Preti fb Fx + 2, 4 D	Preti fb Fx	Weedy	Pre fb Fx + 2,4D	Pret fb Fx	Weedy
DSR	23.0	34.9	501.3	15.0	20.0	315.0
NPTR	30.4	84.3	479.5	81.0	90.0	214.0
PTR	30.6	47.8	387.2	14.0	23.0	75.0
NWSR	20.8	60.2	583.0	68.0	76.0	332.0
WSR	29.2	31.1	463.0	13.0	23.0	73.0
LSD$_{0.05}$		105.0			111.1	

In our study, without weed control, the maximum weed density and biomass was produced in DSR and NWSR while the minimum was recorded in PTR. Herbicide efficacy was better in DSR and WSR than in the other planting methods. The effect of herbicide was similar in both seasons. Between the two herbicide treatments used, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D produced a lower weed biomass compared to pretilachlor followed by fenoxaprop plus ethoxysulfuron in all the planting methods. This response was because of the addition of 2,4-D which provided additional control of broadleaved weeds. Similarly, in a previous study, herbicide combinations or herbicide plus hand weeding provided excellent control of weeds than the single application of herbicides (Sangeetha et al., 2011). In this study, the application of pretilachlor plus safener at 5 DAS followed by hand weeding at 45 DAS registered significantly lower total weed density and weed biomass compared with the weedy check, which could be due to the effective control of weeds at the early stages of crop growth by pretilachlor plus safener. Pretilachlor plus safener at 5 DAS followed by hand weeding at 45 DAS recorded the highest weed control efficiency of 67%, which was comparable with cyhalofop-butyl at 15 DAS followed by hand weeding at 45 DAS and hand weeding twice at 20 and 45 DAS. Similar results were reported by Raju et al. (2001) and Subramanian (2003).

Yadav et al. (2008) reported that there was an inconsistency in weed infestation among direct-seeded treatments; the lowest total weed biomass was observed in WSR plots and the highest in DSR in the first year but in the second year, these results were reversed. In a recent study, Sheeja et al. (2013) reported that, among different establishment techniques, mechanized transplanting with cono-weeding at 15, 30, and 45 DAT recorded the highest weed biomass accumulation. In another study in Pakistan, an early postemergence application of herbicide provided effective weed control at the early stage of crop growth, which resulted in low weed biomass (Ehsanullah Akbar et al., 2007). While comparing the treatments, it was observed that the total weed biomass was higher in direct seeding than in transplanting. Our results are in line with earlier studies in confirming higher total weed biomass in wet seeding than transplanting. The reasons were that weeds that emerged early were controlled by the early application of

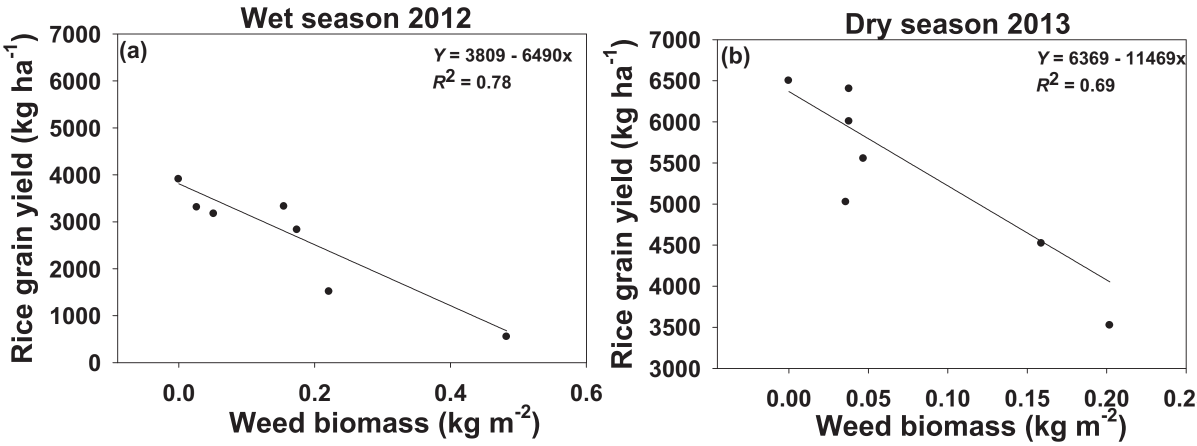

Fig. 9. Relationship between weed biomass (kg m^{-2}) at flowering and rice grain yield (kg ha^{-1}) in the wet season of 2012 (a) and dry season of 2013 (b).

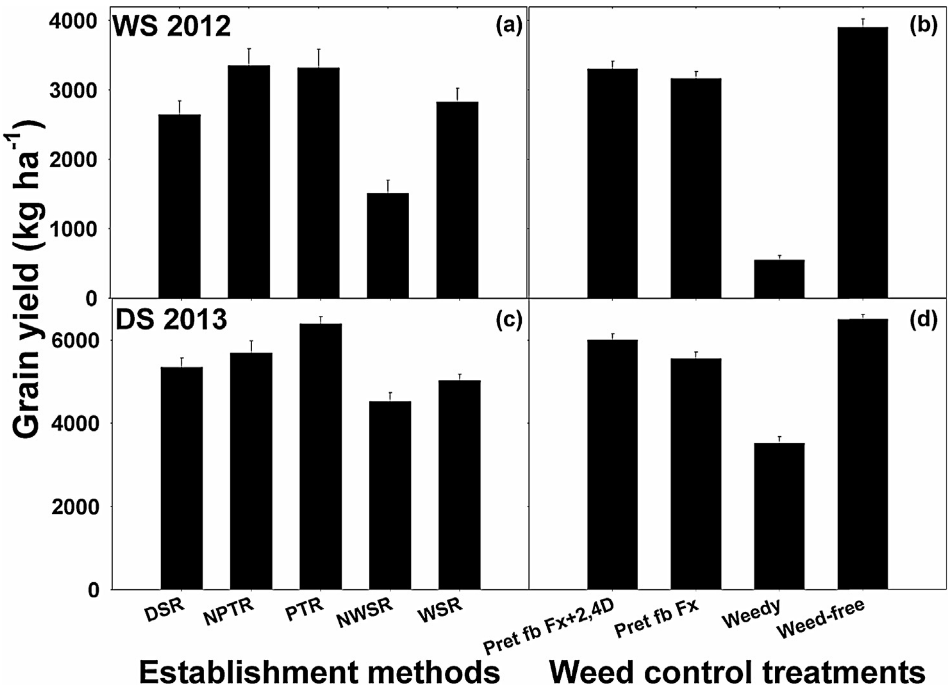

Fig. 10. Effect of rice establishment methods (DSR, dry drill seeded rice; NPTR, transplanting after dry tillage; PTR, transplanting after puddling; NWSR, wet drum seeding after dry tillage; and WSR, wet drum seeding on puddled soil) (a, c) and weed control treatments (Preti fb Fx plus 2,4D, pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D; Preti fb Fx, pretilachlor followed by fenoxaprop plus ethoxysulfuron; and weedy) (b, d) on rice grain yield in the wet season of 2012 (WS 2012) (a, b) and dry season of 2013 (DS 2013) (c, d).

postemergence herbicides and that the seedlings were planted at proper spacing in transplanted rice (Budhar and Tamilselvan, 2002; Singh and Singh, 2010). In another study in Pakistan, weedy check plots had significantly higher weed biomass (65–274 $g\,m^{-2}$) than the herbicide-treated plots (36–142 $g\,m^{-2}$) in PTR and WSR (Baloch et al., 2006). WSR, with and without weed management, had higher weed biomass (59 and 249 $g\,m^{-2}$) than the transplanted culture (19 and 67 $g\,m^{-2}$).

Our results showed that under weed-free conditions, rice grain yield in DSR was at par with the yield obtained in PTR and NPTR. Among the weed management treatments, the plots treated with pretilachlor followed by fenoxaprop plus ethoxysulfuron and pretilachlor followed by fenoxaprop plus ethoxysulfuron plus 2,4-D produced higher yields than the weedy check but were similar to the weed-free plots. Similar results were reported in a previous study, in which plots treated with the combination of one herbicide application plus a single hand weeding provided effective weed control and had fewer weeds than the two hand weeding treatment (Timsina et al., 2010). Compared with the weed-free plots, the weedy check plots of the zero-till DSR had yield losses of 12% compared with the 14% losses in PTR and 40% losses in the conventional-till DSR. DSR in zero-till conditions produced the highest yield (6.28, 6.65, and 7.11 $t\,ha^{-1}$) as compared to DSR in conventional tillage (3.92, 6.98, and 6.48 $t\,ha^{-1}$) and transplanted rice (5.24, 5.4, and 6.08 $t\,ha^{-1}$) in the weedy, two hand weeding, and one herbicide application followed by one hand weeding treatments, respectively (Timsina et al., 2010). Sangeetha et al. (2011) reported that drum seeding produced a higher grain yield (4099 $kg\,ha^{-1}$) than broadcasting (3842 $kg\,ha^{-1}$) across different weed management practices and that the plots treated with pretilachlor plus safener at 5 DAS followed by hand weeding at 45 DAS recorded a higher grain yield (5155 $kg\,ha^{-1}$) than other treatments [cyhalofop-butyl at 15 DAS followed by hand weeding at 45 DAS (4629 $kg\,ha^{-1}$) and hand weeding twice at 20 and 45 DAS (4695 $kg\,ha^{-1}$)].

5. Conclusions

The results of our study demonstrate that DSR can produce yields comparable with that of PTR, provided that weeds are properly controlled. The use of a combination of postemergence herbicides for grass, sedge, and broadleaved weeds provided higher yield than the application of a single postemergence herbicide. Without any control measure, weed pressure was higher in DSR and WSR than in PTR. Grasses were higher while sedges and broadleaved weeds were lower in DSR as compared to PTR and NPTR. In both seasons, herbicide efficacy was better in DSR and WSR than in the other establishment methods.

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