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Integrated weed management in direct-seeded rice: dynamics and economics

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Abstract

Weeds are often the most severe problem in direct-seeded rice (*Oryza sativa* L.) (DSR), cause reductions in yield and profitability. The traditional method of controlling rice weeds or manual weeding has several demerits as the practice is uneconomical and difficult. The effects of 10 different weed management practices were evaluated to identify the most effective and economical method of managing weeds in DSR in Nepal during the rainy season of 2010. Pendimethalin was applied pre-emergence where 2,4-D, bispyribac sodium, and oxadiargyl were applied post-emergence alone or combined with hand weeding. Sesbania (*Sesbania aculeata* Wild. Pers.) was co-cultured with rice and killed by with using 2,4-D. Weed emergence, density, and biomass per unit area of 3 weed types: broadleaf, sedges, and grasses were assessed during 20, 40, 60 days after seeding (DAS), and at harvest. Treatments were compared either to weedy check or weed-free control to determine weed control indices. A total of 42 weed species belonging to 27 genera and 11 families emerged across the growing season of rice. Most of the weeds were annual where broadleaf and sedges were dominant during the first two months, and grasses were dominant under flooding. Weeds reduced the rice yield by more than 80% in weedy-check with respect to weed-free control. A sequential application of pendimethalin as pre-emergence and bispyribac-sodium postemergence herbicides followed by a hand weeding at 45 DAS provided up to 85% weed control over weedy check than other weed control measures. However, that method found uneconomical when compared to the same without hand weeding because of the high cost of manual labor. Pendimethalin was effective in controlling early flush of weeds and bispyribac efficiently controlled weeds even after flooding turned out to be a less expensive method controlling in DSR. An integrated approach of weed management including both pre-emergence and post-emergence herbicides can provide season-long weed control greater economic return.

Keywords: Direct-seeded rice, Weeds, Herbicides, Hand weeding, Benefit to cost ratio

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Introduction

In Nepal, rice (*Oryza sativa* L.) is widely planted manually by transplanting 20 to 30-days-old seedlings into puddled soil. However, transplanting is becoming increasingly challenging due to unavailability and the high cost of labor and energy, restricted supply of irrigation water, and decline of soil quality (Chauhan, 2012b). Depending on the growing season, climatic conditions, soil types, and hydrological condition, the total seasonal water input for a puddled transplanted rice ranges from 660 to 5280 mm (Bouman and Tuong, 2001). As a result, DSR is gaining in popularity as it is an economical alternative to transplanted rice. Direct-seeding of rice on pulverized soil reduces total labor requirement by 11 to 66%, saves 19 to 24 person-d ha-1, resulting in earlier and easier crop establishment (Rashid et al., 2009). DSR has the potential to reduce water and labor use compared to transplanted rice by eliminating the puddling phase and avoiding continuous standing water (Kumar and Ladha, 2011). Direct seeding reduces irrigation requirements by 30% of the total irrigation water required for transplanted rice (1400 to1800 mm) (Gopal et al., 2010), and results in greater tolerance or rice to water deficit (Yadav et al., 2004). Also, DSR matures 8 to11 d earlier than transplanted rice, which facilitates the earlier establishment of the following winter wheat (Balasubramanian and Hill, 2000).

Despite several advantages, weeds are considered a major biological constraint of DSR systems (Dhakal et al., 2015; Chauhan, 2012a), resulting in inferior yields and poor stand establishment compared to transplanted rice (Singh et al., 2005). More than 50 weed species reported to be a significant cause of yield loss in DSR (Gianessi et al., 2002). It was estimated that rice yields were reduced by 80% (Mahajan et al., 2009), and even up to 100% in DSR compared to transplanted rice when no weed management practices were implemented (Sharma et al., 1977). Weeds compete with rice for light, nutrients, and water, ultimately diminishing crop growth and development. Singh and Dash (1988) reported that an increase in dry weed biomass at the

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rate of 1 g m^{-2} decreased rice yield by 7.4 kg ha^{-1}. The weed interference early in an establishment is especially problematic in DSR owing to the size disadvantage of seedlings relative to weeds and soil water deficit condition. Weeds cause reductions in crop quality by interfering with rice harvest and sometimes makes mechanical harvest impractical. Cyperaceae and Poaceae are predominant, out of 1800 species reported as weeds of rice (Moody, 1989). Dominant weed species in South Asia include *Cyperus rotundus, Fimbristylis miliacea, Ischaemum rugosum, Monochoria vaginalis*, *Comellina* spp., *Echinochloa* spp., *Cynodon dactylon*, *Elucine indica*, in DSR system (Chauhan, 2012b).

Suppression of weeds very early in the season holds the key for a successful DSR (Singh, 2008) as it is described as 'knowledge intensive' practice because of its requirement of a more decisive role in crop management and weed control. Substantial information is required to enable farmers to judge the best scientific options for weed management, especially during the transition from transplanting to direct-seeding (Rao et al., 2007). In Nepal, manual weeding is extensively practiced, which usually starts from 20 to 30 DAS, only after the weeds have reached a sufficient size to be pulled (Rao et al., 2007). But it may trigger late to catch the critical crop-weed competition which is evidenced by yield loss assessments of the effects of manual weeding at 20 to 30 DAS with selective herbicides (Zimdahl, 1999). Labor scarcity, high labor cost, identical growth of weedy grass and rice seedlings, and the presence of perennial weeds that breakout on pulling may all lead to lowered efficacy in manual weeding (Rao et al., 2007).

Use of herbicides is one of the alternatives of manual weeding (Rao et al., 2007) which in recent years has been dramatically increased in South Asia by the spread of DSR (Azmi et al., 2005). Application of pre-emergence herbicide is effective at dry period for early flush of weeds either just before or after rice emergence (Singh et al., 2016; Mahajan and Chauhan, 2015), but for the second flush of weeds at the flood period requires either a post-emergence herbicide application or manual weeding (Jordan et al., 1998). The narrow time window (0 to 3 DAS) demands highly effective pre-emergence herbicides (Mahajan and Chauhan, 2015) to provide season-long weed control (Helms et al., 1995) such as pendimethalin, quinclorac, and thiobencarb. Bispyribac-sodium (bispyribac from now on), 2,4-D, clomazone, halosulfuron, fenoxaprop are the common post-emergence herbicides used to control selective weeds (Rao et al., 2007). Although, oxadiargyl, a protoporphyrinogen inhibitor is a pre-emergence herbicide, which can also be applied either delayed pre-emergence or early post-emergence. Oxadiargyl was found effective in some regions of India and Nepal in controlling grassy weeds (Gopal et al., 2010). The effectiveness of herbicide is limited by its diverse interacting factors such as diverse weed species, weed populations, cultural practices, soil and climatic conditions, and development of herbicide resistance (Moody, 1991). The use of single herbicide may not work for more extended period which often demands change in herbicide mixture in a few years or integration with mechanical methods. We hypothesized that incorporation of pre-emergence and post-emergence herbicide followed by manual weeding is the efficient and economical approach to weed management in DSR. Therefore, the objectives of this research were to 1) describe weeds and their diversity in DSR, and 2) quantify weed density and biomass in response to management practices. Outcomes will contribute, to developing effective weed management strategies for DSR.

Materials and Methods

Study Location

A field experiment was conducted at the Agronomy Research Farm (27.6474^{0}N, 84.3497^{0}E) of the Institute of Agriculture and Animal Science located in Chitwan district of Nepal during the rainy season of 2010. The region is subtropical, with annual average precipitation of about 1620 mm (90% occurs from June to September) (Thapa and Dangol, 1988). The total rainfall received from May to November was 1350 mm with a peak in July (490 mm). The average maximum and minimum temperatures recorded from May to November were ranged from 27.8 to 35.5 and 17.7 to 26.9^{0}C, respectively (NMRP, 2011) (Fig. 1).

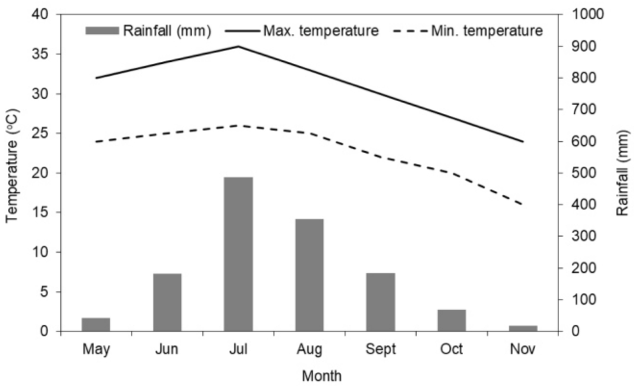

Figure 1. Temperature and rainfall for the seven months period of 2010 recorded at nearby weather station of research location at Chitwan, Nepal.

The soil texture was sandy loam (sand = 60.4 ± 4.4%, silt = 27.3 ± 2.7%, and clay = 12.3 ± 1.2%). The top 20 cm soil was low in organic matter content (2.34 mg g^{-1}) with a slightly acidic pH range of 5.8 – 6.4. Historically, the area was known as the Narayani River floodplain and 'rice superzone area' stated by the government of Nepal. The field was previously fallowed for more than one year and rich in the annual weed seed bank.

Experimental Design and Treatments.

Ten weed management practices including pre-emergence and post-emergence herbicide (Table 1) were evaluated in a randomized complete block design with three replications. Herbicides included in the study were pendimethalin (Stomp® 3.3EC, BASF India Ltd.), 2,4-D (Suspend® 80WP, CACP Ltd. India), bispyribac-sodium (Nominee gold® 10SC, PI Industries), and oxadiargyl (Topstar® 80WP, Bayer Crop Science). The experimental unit consisted of 3 × 4 m (12 m^2) plot, accessed to the controlled surface irrigation system.

Experimental Details

A blanket application of glyphosate (Glykal 41SL, Kalyani Industries Pvt. Ltd.; 1.5 kg ai ha^{-1}) was performed in the first week of May followed by a crisscross plowing with a disc harrow followed by single planking. A light pre-sowing irrigation (10 cm) was provided, 48 h before seeding. The rice cultivar planted was 'Sabitri,' a fine, semi-dwarf (grow up to 1 m tall) which was derived from the cross of IR 1561-228-1/IR 1737//Cr 94-13 (Poudel, 2007). The seed was pre-treated with carbendazim® (Bavistin, 50%WP, Biostadt India Ltd., Mumbai) at a rate of 0.5 g ai kg^{-1}, and hand-seeded in the first week of June at a rate of 40 kg ha^{-1} in light, moist soil at 20 cm row spacing, placed at 2-3 cm deep. The soil was leveled with hand and slightly packed to facilitate germination. On the same day, a legume *Sesbania aculeata* Wild. Pers., native to Asia and North Africa, was co-seeded with rice at a rate of 30 kg ha^{-1}. Fertilizers, 50 kg N, 25 kg $ZnSO_4$ and 30 kg P and K were incorporated into the soil as a basal dose. An additional 50 kg ha^{-1} of N was top-dressed in two splits at 40 and 60 DAS. The field was flooded at 7 days interval prior to the field permanently flooded after an intense rain (> 300 mm) on the third week of July. A detail of applied treatments with their timing and rate of application is provided in Table 1. Pendimethalin was applied as pre-emergence at the rate of 3.3 L ha^{-1}, a few hours after seeding rice. A delayed pre-emergence application of oxadiargyl at a rate of 112 g ai ha^{-1} was done, one week after seeding. Oxadiargyl powder was mixed with sand (20 kg ha^{-1}) and broadcasted similar to a general practice of farmers. All plots were irrigated not more than 3 cm just before oxadiargyl application. Bispyribac and 2,4-D were applied as post-emergence from 20 to 22 DAS (three-to-four leaf stage of rice), one day after third irrigation at the rate of 25 and 1500 g ai ha^{-1}, respectively. Sesbania was killed by 2,4-D ethyl ester at a rate of 500 g ai ha^{-1} at 25 DAS. A battery operated knapsack sprayer fitted with a double boom nozzle was calibrated to deliver 500 L ha^{-1} for pendimethalin and 350 L ha^{-1} for post-emergence spray solutions. A single application of insecticide Endosulfan 350 EC (Thiodan, now banned) at 1 L ha^{-1} was applied before the milking stage of the crop to control rice Gundhi bug (*Leptocorisa oratorius* F.). Weeds removed manually on targeted plots at 45 DAS preceding chemical treatment whereas weed-free plots weeded weekly throughout the season. The above-ground biomass was harvested in the second week of September (125 DAS), cut to 8 to 10 cm stubble height using a hand sickle. Harvest was left on the field for 5 day to allow sun drying. Threshing was done manually. Grains were detached cleaned by winnowing and weighed at their ambient moisture level (17%) to determine yield. Similarly, straw was weighed to account for the total biological yield.

Table 1. Details of treatments applied in DDSR plots in 2010.

Treatment ID	Treatment details	Dose g ai ha^{-1}	Application time DAS
W_1	Weedy-check	NA	NA
W_2	Weed-free	NA	Weekly
W_3	Sesbania fb 2,4-D	500	25
W_4	Pend	3300	0§
W_5	Pend fb HW	3300	0 fb 45
W_6	Pend fb 2,4-D	3300 fb 1500	0 fb 22
W_7	Pend fb 2,4-D fb HW	3300 fb 1500	0 fb 22 fb 45
W_8	Pend fb bispyribac	3300 fb 25	0 fb 22
W_9	Pend fb Bispyribac fb HW	3300 fb 25	0 fb 22 fb 45
W_{10}	Oxadiargyl fb HW	112	7 fb 45

fb = followed by, HW = hand weeding, DAS = days after sowing, Pend = pendimethalin

§ Day zero i.e. on a seeding day

Weed Dynamics

Weed samples were collected using destructive sampling technique during 20, 40, 60 DAS, and harvest inside a 50 cm × 50 cm quadrat at three random locations on each plot. Total weeds were then separated into species fractions (broadleaves, grasses, and sedges) and then counted to determine their dominance based on their density (D) and frequency (F). Weeds were identified with the aid of a standard practical field guide by Caton et al. (2010). Local rice growers assisted in identifying some native weeds, especially during the early vegetative stage. Samples were dried for at least 48 h in a forced air oven at 55°C before weighing. The weed species density was calculated as the number of individual plants per unit area, whereas the total weed density was calculated as the total number of weeds per unit area for particular treatment [Eq. 1].

$$\text{Density (plants m}^{-2}) = \frac{\text{number of plants}}{0.25\ \text{m}^2} \quad [1]$$

Frequency was determined as the presence or absence of weed species within the quadrat. The frequency of individual weed species was determined using a method modified from Misar et al. (2016):

$$\text{Frequency (\%)} = \frac{\text{no. of quadrats containing at least one plant}}{\text{total N of quadrats (90)}} \times 100 \quad [2]$$

Weed control efficiency (WCE) was determined for each treatments using Eq. [6] given by Mani et al. (1973) which expresses the percentage reduction in weed population due to weed control methods over the unweeded check.

$$\text{Weed control efficiency (\%)} = \frac{WP_c - WP_t}{WP_c} \quad [3]$$

where WP_c is weed population (plants m^{-2}) in an unweeded plot and WP_t is the population in the treated plot. Weed index (WI) was determined for each treatment as the reduction in grain yield due to the presence of weeds in comparison with no weed plot. Crop grain yield was determined and corrected to 12% moisture. Weed index was calculated as suggested by Gill and Vijay Kumar (1969) using Eq. [4].

$$\text{Weed index} = \frac{X - Y}{X} \times 100 \quad [4]$$

Where X and Y are the crop grain yield (Mg ha^{-1}) from weed free plot and treated plots, respectively.

Economic Analysis

Cost of cultivation was calculated from current local charges for different agro-inputs such as labor, fertilizer, compost, diesel, electricity, and farm equipment including 5% contingency measures. Similarly, gross return was determined for the economic yield (grain + straw) of rice on the basis of the current local market price.

Then benefit to cost ratio was determined as the ratio of gross return to the cost of cultivation [Eq. 5] which also expressed as the return per dollar (transacted in rupee) invested (Reddy and Reddi, 2002). B:C ratio greater than 2.0 would consider economically ideal for farm business management for most of the agricultural commodities. That means farmers would get $ 2.0 for every dollar invested.

$$\text{B:C ratio} = \frac{\text{Gross return (USD)}}{\text{Total cost of cultivation (USD)}} \quad [5]$$

Statistical Analysis

Weed density or count data were square root transformed $\sqrt{(x+1)}$ before analysis because they were discrete and the distribution was right-skewed. The weed frequency distribution was binomial. Thus, the GLIMMIX procedure was used to analyze the data in SAS 9.4 (SAS Institute, Cary, NC) where the default link function was 'logit' (Stroup, 2015). Treatments were set as fixed effects and replication was configured as a random effect (Littell et al., 2006). Treatment means were compared at α = 0.05 using Least Significant Difference test at $P \leq 0.05$.

Results and Discussion

Weed Emergence

A total of 42 weed species belonging to 27 genera within 11 families were identified across the growing season of rice on the field (Table 2). The dominant weed species observed were belonging to the Poaceae family (15 spp.) followed by Cyperaceae (13 spp.), Compositae (3 spp.), Amaranthaceae and Commelinaceae (2 spp. each) and others (7 spp.). Overall, 13 broadleaf weed (BLW), 14 sedges, and 15 grass species were recorded in the field. Based on density and frequency, the dominant weed species were *Echinochloa colona* (L.) Link, *Digitaria ciliaris* (Retz.) Koel., *Paspalum brevifolium* Flugge, *Cynodon dactylon* Pers., *Ischaemum rugosum* Salisb., and *Eleusine indica* (L.) Gaertn. among grasses; *Commelina benghalensis* L., *C. diffusa* L., and *Monochoria vaginalis* Burm. among the broadleaf and *Fimbristylis miliacea* Vahl., *Scirpus juncoides* Roxb., and *Cyperus* spp. among the sedges.

Table 2. Description of the observed weed species, their emergence time, population density, and frequency in DSR. Density and frequency of weeds were averaged over multiple sampling dates and replications.

Scientific name	Family	Group	Density	Frequency	Emergence time			
					20	40	60	H
			Plants m^{-2}	%	DAS			
Aeschynomene indica L.	Fabaceae	Broadleaf	3	6	–	+	–	–
Ageratum conyzoides L.	Compositae	Broadleaf	4	11	+	+	+	–
Alternanthera sessilis R. Br.	Amaranthaceae	Broadleaf	3	7	–	+	+	–
Amaranthus viridis L.	Amaranthaceae	Broadleaf	2	4	+	–	–	–
Caesulia axillaris Roxb.	Compositae	Broadleaf	8	8	+	+	+	+
Centella asiatica (L.) Urb.	Apiaceae	Broadleaf	3	4	–	–	+	+
Commelina benghalensis L.	Commelinaceae	Broadleaf	94	97	+	+	+	+
Commelina diffusa L.	Commelinaceae	Broadleaf	32	64	+	+	+	–
Euphorbia hirta L.	Euphorbiaceae	Broadleaf	7	17	+	+	+	+
Ipomoea aquatica Forsk.	Convulvulaceae	Broadleaf	4	22	–	+	+	–
Melochia corchorifolia L.	Sterculiaceae	Broadleaf	2	12	+	+	–	–
Monochoria vaginalis Burm.	Pontederiaceae	Broadleaf	9	14	–	+	+	–
Phyllanthus fraternus Webs.	Euphorbiaceae	Broadleaf	5	11	+	+	–	–
Bulbostylis barbata Clarke	Cyperaceae	Sedge	7	7	–	–	–	+
Cyperus brevifolius Hassk.	Cyperaceae	Sedge	2	10	+	+	–	–
Cyperus compressus L.	Cyperaceae	Sedge	1	9	–	+	–	–
Cyperus difformis L.	Cyperaceae	Sedge	47	56	–	+	–	–
Cyperus esculentus L.	Cyperaceae	Sedge	2	4	–	+	+	–
Cyperus flavidus Retz.	Cyperaceae	Sedge	4	6	–	–	+	+
Cyperus halpan L.	Cyperaceae	Sedge	14	20	+	+	+	–
Cyperus iria L.	Cyperaceae	Sedge	4	2	–	+	+	–
Cyperus pilosus Vahl.	Cyperaceae	Sedge	3	3	–	+	–	–
Cyperus rotundus L.	Cyperaceae	Sedge	117	96	+	+	+	+
Fimbristylis dichotoma Vahl.	Cyperaceae	Sedge	6	4	–	+	+	–
Fimbristylis miliacea Vahl.	Cyperaceae	Sedge	43	39	–	+	+	+
Scirpus juncoides Roxb.	Cyperaceae	Sedge	55	37	–	–	+	+
Scirpus mucronatus L.	Cyperaceae	Sedge	9	4	–	+	+	+
Brachiaria ramosa Stapf.	Poaceae	Grass	15	10	+	+	–	–
Chrysopogon aciculatus Retz.	Poaceae	Grass	7	10	+	+	+	–
Cynodon dactylon Pers.	Poaceae	Grass	25	22	+	+	+	+
Dactyloctenium aegyptium L.	Poaceae	Grass	11	11	+	–	–	–
Digitaria ciliaris (Retz.) Koel.	Poaceae	Grass	58	54	+	+	–	–
Echinochloa colona (L.) Link	Poaceae	Grass	109	70	+	+	+	–
Echinochloa crusgalli L.	Poaceae	Grass	4	3	+	+	–	–
Eleusine indica (L.) Gaertn.	Poaceae	Grass	23	22	–	+	+	+
Eragrostis tenella P. Beauv.	Poaceae	Grass	12	13	+	+	–	–
Ischaemum rugosum Salisb.	Poaceae	Grass	3	3	+	+	–	–
Leersia hexandra Sw.	Poaceae	Grass	11	11	–	–	+	–
Paspalum brevifolium Flugge	Poaceae	Grass	26	24	+	+	+	–
Paspalum scrobiculatum L.	Poaceae	Grass	2	4	+	+	+	–
Setaria glauca (L.) P. Beauv.	Poaceae	Grass	8	3	+	–	–	–
Seteria pallid–fusca Schum.	Poaceae	Grass	13	7	–	–	+	–
Total number of species = 42	Family = 11		N = 817					

H, harvest; DAS, days after sowing; N, total number of weeds m^{-2}

Grasses dominated weed flora as they comprised 41% of the total weed population whereas BLW and sedges consisting of 37% and 22%, respectively. Grasses were emerged as early flush and abundant although the density was not significant than sedges and broadleaf because of the previous seed bank of grasses and appropriate moisture content of the soil as the field was non-flooded for the first month of seeding. At 40 DAS, all categories of weeds appeared in equal proportion. The third flush of weed was counted at 60 DAS after the hand weeding on 45 DAS, mostly characterized by broadleaf and sedges as the grass population started to decline due to standing water in the field. Broadleaves such as *Monochoria vaginalis* Burm. emerged significantly after continuous irrigation whereas *Commelina* spp. began decreasing continuously but appeared throughout the season. *Cyperus rotundus* L. was the most frequently observed weed followed by *Echinocloa colona* (L.) Link and *Commelina benghalensis* L.

Weed species such as *Cynodon dactylon* L., *Cyperus* spp., and *Commelina* spp. may emerge earlier when they receive adequate soil moisture. Pendimethalin applied pre-emergence controlled a significant number of broadleaf and sedges but didn't show any effect on *Cynodon dactylon* L. and *Echinocloa* spp., which were even flush out significantly, two weeks after sowing. Sedges and grasses were dominant in 2,4-D applied plots. Sesbania co-culture was effective against grasses, broadleaf, and few sedges. Almost all families of weeds observed in control and oxadiargyl treated plots. In control plots, broadleaf comprised nearly 65% of all the species. Bispyribac favored sedges while *Cynodon dactylon* L. consistently appeared in plots treated with pendimethalin alone and oxadiargyl.

The primary reason that affects the dynamics of weed population emergence and its subsequent establishment depends on many new recruitments as a fresh seed rain or existing weed-seed bank (Naylor, 2002). Singh (2008) reported that broadleaf weeds dominated the first 30 DAS than grasses and sedges, constituting more than 62% of the total weed composition and indicated emergence from the pre-existing seed bank. Singh et al. (2016) reported 50% ground coverage owing to broadleaf weeds followed by grasses (15%) and sedges (5%) at 45 DAS. Kim et al. (1997) also recorded similar types of weed species in DSR where annual grasses were the predominant weeds, such as *Echinocloa* spp., *Digitaria adscendens* (Kunth) Henrard, *Leptochloa chinensis* L., and *Setaria viridis* (L.) P. Beauv., including weedy rice (*O. sativa* L. subspp. *spontanea*). Sedges and grasses can survive continuous flooding to a water depth of 10 cm; however, in our study, a week of flooding during peak monsoon eliminated some grass and broadleaf species. At harvest, the majority of grasses were disappeared from all plots except on control, which had a thin stand of a crop. The weed community was so diverse that only integrated approach of management would give satisfactory results, enough to justify the treatments applied.

Weed Density

Weed management strategies affected the total weed population density across the rice growing period (Table 3). Pendimethalin was superior in controlling early flushes of weeds at 20 DAS. Bispyribac and 2,4-D were equally effective following pendimethalin in reducing postemergence weeds at 40 and 60 DAS even without additional hand weeding. Pendimethalin alone, sesbania co-culture, and oxadiargyl couldn't suppress weed population during mid and late season when the second flush of weed emerged after flooding rice field. Most of the sedges appeared after the first hand-weeding showed greater weed density in plots treated with pendimethalin than broadleaf and grasses. Bispyribac effectively killed deep-rooted sedges as they resist manual weeding because of their breakable culm and deep-set of knots. Post-emergence herbicides, 2,4-D, and bispyribac provided excellent control of weeds starting 20 DAS up to harvest. Combination of hand weeding provided an opportunity to remove grassy weeds where grasses tended to survive post-emergence herbicide, especially *Cynodon dactylon* L.

Table 3. Total weed population as affected by different weed management practices during 20, 40, 60 DAS, and harvest of DSR in Chitwan, Nepal.

Treatment	Total weed density			
	20 DAS †	40 DAS	60 DAS	Harvest
	plants m^{-2}			
Weedy-check	784 a§	1000 a	557 a	189 a
Weed-free control	-	-	-	-
Sesbania followed by 2,4-D	613 b	352 c	225 b	160 b
Pendimethalin	229 d	529 b	248 b	136 c
Pendimethalin followed by HW	274 d	581 b	101 cd	41 fg
Pendimethalin followed by 2,4-D	244 d	315 cd	221 b	96 d
Pendimethalin followed by 2,4-D followed by HW	223 d	305 cd	126 c	56 ef
Pendimethalin followed by bispyribac	216 d	186 e	80 cd	102 d
Pendimethalin followed by bispyribac followed by HW	273 d	244 de	52 de	26 g
Oxadiargyl followed by HW	396 c	524 b	86 cd	64 e
LSD ($P < 0.05$)	113	76	63	16
Mean	325	404	170	87

† DAS, days after seeding
HW, hand weeding
§ Treatment means followed by different lowercase letters are different at $P < 0.05$.

Weed density and biomass determine the extent of crop-weed interference, yield, and quality of the harvest. An effective weed management method should ensure a weed density and biomass below an economic threshold (IRRI, 1967). Sesbania co-culture reduced the plant density by 50% as compared to weed-free plot and created an environment favorable for weeds. Singh et al. (2007) reported that *Sesbania* intercropping caused a 37% reduction in total weed biomass at 75 DAS. Controlling late flushes of weeds with postemergence herbicides such as bispyribac and 2,4-D gave superior results. Hussain et al. (2008) reported that among four herbicidal treatments viz. SunStar Gold 60 WG at 200 g ha^{-1}, a rice field treated with a postemergence application of bispyribac applied at 15 and 25 DAS produced the lowest weed biomass when compared to pre-emergence herbicides. Suria et al. (2011) reported that pendimethalin treated plots had the lowest (80 plants m^{-2}) weed density than control. Singh et al. (2016) reported the lower weed density in plots treated with pendimethalin (10 to 13 plants m^{-2}) at 20 DAS than others because of the lowest record of broadleaf weeds and sedges. Oxadiargyl caused necrosis of rice leaves and increased tiller mortality that reduced the ability of rice to suppress weeds. In a greenhouse experiment, Gitsopoulos and Froud-Williams (2004) reported a significant rice crop sensitivity to oxadiargyl when applied at more than 100 g ha^{-1} under dry seeding. Dario and Gallo (1999) noted similar phytotoxic symptoms such as stunting of rice plants, slower growth and brown spots on the main culm and leaf up to 60 DAS in Brazil. It was also reported that bispyribac at the rate of 25 g ha^{-1} provided excellent control of grasses and sedges, and total weeds (Schmidt et al., 1999). Mahajan and Chauhan (2015) reported lower sedges density (5 plants m^{-2}) in the plots treated with bispyribac at 25 g ha^{-1} compared to 32 and 29 plants m^{-2} in plots treated with pendimethalin and fenoxaprop, respectively. Similar result was reported by Ranjit and Suwanketnikom (2005) and Gill et al. (1996) where they found excellent control of grass (*Echinochloa* spp.) and sedges (*Cyperus* spp.) using bispyribac at higher rates (25-30 g ha^{-1}) at an early application timing (15-20 DAS).

Weed Biomass

Dry biomass is the best way of expressing weed dominance as this method is less sensitive to the sampling frame than density. For example, a single culm of *Commelina* spp. may equal tens of *Fimbristylis* spp. with respect to biomass. Biomass provides information about the accumulation of the growth and use of nutrients from the soil. The biomass of grasses, broadleaf, and sedges was lower with 2,4-D and bispyribac alone or in integration with manual weeding compared to weedy check, sesbania co-culture, pendimethalin only, and oxadiargyl (Table 4). A sequential application of 2,4-D or bispyribac following pendimethalin equally reduced the total weed biomass greater than pendimethalin alone, oxadiargyl, and sesbania co-culture. Integrated weed control by combining pre- and post-emergence herbicides and hand weeding, effectively controlled the weed biomass throughout the season.

Table 4. Total weed biomass as affected by different weed management practices during 20, 40, 60 DAS, and harvest of DSR in Chitwan, Nepal.

Treatment	Total weed biomass 20 DAS †	40 DAS	60 DAS	Harvest
	g m^{-2}			
Weedy-check	163.8 a§	340.6 a	224.2 a	48.8 a
Weed-free control	0.0 d	0.0 f	0.0 e	0.0 h
Sesbania followed by 2,4-D	147.8 a	114.0 c	85.4 b	36.2 b
Pendimethalin	51.1 c	187.4 b	102.6 b	28.8 c
Pendimethalin followed by HW	51.9 c	193.7 b	40.7 cd	8.7 f
Pendimethalin followed by 2,4-D	44.1 c	107.6 cd	86.0 b	21.8 d
Pendimethalin followed by 2,4-D followed by HW	43.3 c	95.4 cd	51.5 c	11.8 ef
Pendimethalin followed by bispyribac	43.2 c	62.8 e	38.5 cd	19.1 d
Pendimethalin followed by bispyribac followed by HW	51.3 c	83.1 e	21.9 de	4.8 g
Oxadiargyl followed by HW	91.2 b	188.1 b	35.1 cd	14.2 e
LSD (P < 0.05)	24.1	29.0	24.8	3.9
Mean	68.7	137.5	68.7	19.5

† DAS, days after seeding
HW, hand weeding
§ Treatment means followed by different lowercase letters are different at P < 0.05.

Bispyribac was found superior in controlling sedges, grasses and total weed biomass than others at 60 DAS indicated that it could work even at standing water. The post-emergence application of 2,4-D was found effective in controlling broadleaf weeds comparable with the bispyribac. Sesbania co-culture and a single application of pendimethalin were found weaker in reducing weed infestation throughout the season. Oxadiargyl followed by hand weeding performed in between pre-emergence and post-emergence herbicides. Hand weeding gave added benefits to the herbicide application although it is considered uneconomical. A single application of pre or post-emergence herbicide may not result in superior outcome. Singh et al. (2016) who reported initial effectiveness of pre-emergence herbicides such as pendimethalin and oxadiargyl alone but their performance declined 45 DAS. The post-emergence application of bispyribac and azimsulfuron was found superior either applied alone or in sequential with pre-emergence in controlling all kinds of weeds throughout the season. The grass component in the weed community increased significantly after one month of seeding. Mahajan et al. (2009) also found that the subsequent application of pendimethalin at 1 kg ha^{-1} followed by bispyribac at 30 g ha^{-1} applied 15 DAS resulted in significant control of weeds in DSR. Walia et al. (2008) also reported pendimethalin at 750 g ha^{-1} followed by bispyribac 25 g ha^{-1} resulted in a 372% increase in rice grain yield than weedy-check. McCauley et al. (2005) also observed that without supplementation of post-emergence herbicide with the pre-emergence the chances of crop yield reduction can be increased from 9 to 60% compared to a weed-free condition. Singh et al. (2005) emphasized the importance of the sequential application of pendimethalin as pre-emergence and chlorimuron + metsulfuron as post-emergence in realizing reduced grass population. The research results are in line with the previous studies of superior weed management in direct seeded rice with the application of pendimethalin followed by bispyribac (Mahajan and Chauhan, 2013; Ganie et al., 2013). The sequential application of pendimethalin and 2,4-D was also found superior comparable with the bispyribac. The results also indicated that one hand weeding had an added benefit of realizing weed control in combination of herbicides. Current results are in line with Mann et al. (2004) who reported effective control of weeds with pendimethalin followed by 2,4-D in DSR. Although this research found sesbania co-culture inferior in controlling weeds than other methods, Ghosh et al. (2017) observed significant weed control by sesbania co-culture, 65% more weed control than weedy-check when followed by pendimethalin and then 2,4-D. Combining pre- and post-emergence herbicides in a sequence may provide effective weed control in DSR.

Weed Control Efficiency and Weed Index

The WCE and WI for the entire growing season were compared among treatments (Fig. 2). Sesbania co-culture was found the weakest among the treatments which had only 37% efficiency in controlling weeds. Similarly, pendimethalin alone was also ineffective in controlling the weeds. In contrast, integrated weed control combining both pre- and post-emergence herbicides along with hand weeding resulted in WCE ranged from 77 to 88%. The sequential application of pendimethalin followed by either bispyribac or 2,4-D resulted in inferior results than the additional hand weeding. Oxadiargyl showed greater WCE than pendimethalin alone and the sesbania co-culture. The WI or reduction in yield due to crop-weed competition ranged from 14% in pendimethalin followed by bispyribac followed by hand weeding to 82 % in weedy check (Fig. 2). The *Sesbania* co-culture with rice showed higher yield reduction similar to oxadiargyl compared to other treatments. The higher weed density and the smothering effect of sesbania to the crop could be the reason for low WCE and a higher WI in the brown-manuring plots.

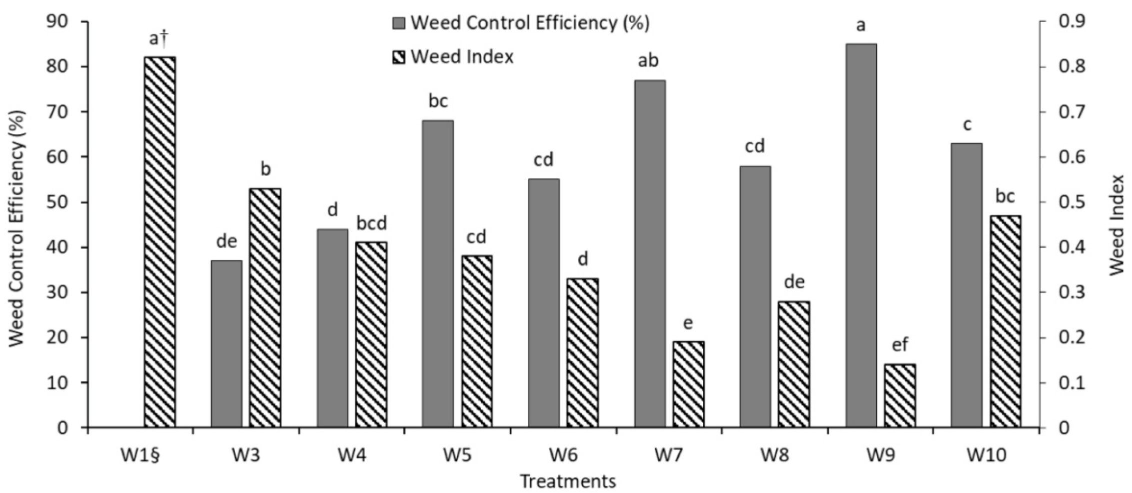

Figure 2. Weed control efficiency and weed index of weed management strategies in DSR at Chitwan, Nepal. § W1, weedy-check; W2, weed-free control; W3, sesbania co-culture; W4, pendimethalin; W5, pendimethalin + hand weeding; W6, pendimethalin + 2,4-D; W7, pendimethalin + 2,4-D + hand weeding; W8, pendimethalin + bispyribac sodium; W9, pendimethalin + bispyribac sodium + hand weeding; Oxadiargyl + hand weeding. † Treatment means followed by different lowercase letters are different at $P < 0.05$.

The efficacy of currently available narrow-spectrum rice herbicides is limited when they are used alone (Singh, 2008; Chauhan, 2012b) and hardly provide season-long weed control (Khaliq et al., 2011). Sesbania co-culture wasn't familiar practice to local growers. One of the reasons highlighted by Kumar et al. (2013) was the smothering effect of sesbania to rice. Singh et al. (2007) reported 20 to 33% lower grass densities and 76 to 83% lower broadleaf densities with sesbania co-culture. The result was supported by Mishra and Singh (2008), who reported lower grain yield (2.37 to 2.67 Mg ha^{-1}) with integration of sesbania with 2,4-D and fenoxaprop compared to other weed control treatments. The higher WI with an early post-emergence application of oxadiargyl was due to reduced yield caused by crop injury from the herbicide treatment. Chauhan (2012b) described oxadiargyl as narrow-spectrum herbicides, reported low efficacy when used alone, and suggested that they do not give season-long weed control. Gitsopoulos and Froud-Williams (2004) reported greater activity of oxadiargyl under wet conditions, and Dickmann et al. (1997) noted that this herbicide can be adsorbed by the soil colloids and can form a shallow herbicidal layer that inhibits weed seed germination. In contrast, Ramana et al. (2007) reported positive results where they found the lowest weed index (8.8%) following oxadiargyl treatment. An integrated approach using herbicides with a different mode of action was advocated by Maity and Mukharjee (2008) to combat weed menaces in DSR and prevent changes in weed community structure where they reported 81 and 86% WCE with integrated weed management during 30 and 60 DAS compared to single applications of pre- and postemergence herbicides. The higher yield can achieve from the consistent reduction of weed population resulting from herbicides integrated with a physical method.

Economic Analysis

Cultivation cost for DSR from field preparation to grain harvest differed among treatments (Table 5). Herbicide application involved the cost of labor and chemical. Hand weeding cost was calculated from person hour needed to do the job. Weed-free control had greater gross and net return but resulted in low B:C ratio due to high cost of production. Weedy-check had a net loss of 191 USD over production cost whereas all weed control treatments were able to provide net positive returns. Among integrated weed control methods, pendimethalin followed by bispyribac and hand weeding had greater value close to 2,4-D preceding pendimethalin and followed by hand weeding. Net return and B:C ratio close to 2 (1.94) were greater with pendimethalin followed by bispyribac than that followed by one hand weeding and other weed control treatments. Sesbania co-culture and oxadiargyl followed by hand weeding had low economic return than other integrated approaches.

Table 5. Cost, gross return, net return, and B:C ratio as influenced by weed management practices in DSR at Chitwan, Nepal. Amount shown are in US dollar.

Treatments	Production cost	Gross return	Net return	B:C Ratio
		$ ha^{-1}		
Weedy-check	413	222 e	-191 g	0.54 e
Weed-free control	898	1171 a	273 c	1.30 c
Sesbania followed by 2,4-D	538	590 d	52 ef	1.10 d
Pendimethalin	488	630 d	142 de	1.29 c
Pendimethalin followed by HW	562	744 cd	182 d	1.32 c
Pendimethalin followed by 2,4-D	521	917 bc	396 b	1.76 b
Pendimethalin followed by 2,4-D followed by HW	605	1033 abc	428 b	1.71 b
Pendimethalin followed by bispyribac	547	1063 ab	516 a	1.94 a
Pendimethalin followed by bispyribac followed by HW	620	1093 ab	473 ab	1.76 b
Oxadiargyl followed by HW	530	609 d	78 e	1.15 d
LSD ($P < 0.05$)	-	147	70	0.15
Grand mean	572	807	235	1.39

HW, hand weeding

§ Treatment means followed by different lowercase letters are different at $P < 0.05$.

One of the advantages of the DSR system had been observed as all the treatments were yielding low to satisfactory (B:C ratio 1.1 to 1.94) levels of economic benefit. The ratio implied that there was at least no loss which would be opposite if the crop was transplanted rice because of the high cost of labor and irrigation. In a study conducted by Dhakal et al. (2015) in Nepal reported that the farmers of 8 districts in Terai region realized lower B:C ratio with transplanted rice as compared to DSR. Pre-emergence application of pendimethalin followed by a post-emergence bispyribac controlled early and late flush of weeds effectively which mirrored into the greater crop productivity and economic returns as compared to the less efficient methods of weed control. The result was in conformity with Hussain et al. (2008), they reported the highest net benefit with the application of bispyribac followed by Sunstar Gold while the lowest net gain was observed at an unweeded-check plot. Hasanuzzaman et al. (2008) reported that the maximum cost of integrated weed control was hand weeding due to the high cost of labor in India. The economic analysis also showed that the application of herbicide maximized the profit and B:C ratio. They also added that herbicidal treatments were more profitable than hand weeding, and maybe an alternative in controlling weeds more easily and cheaply when there is a labor crisis.

Conclusions

The DSR hosted all kinds of weeds across the rice season with a complex mixture of BLW, sedges, and grasses. However, a few weed species such as *Cynodon dactylon* L., *Commelina* spp., and *Cyperus* spp. remained dominant throughout the rice growing period. Weeds can potentially reduce the DSR yield by 82% if not controlled. Herbicides can be effective up to 85% of the weed-free measure if integrated with manual weeding. Pendimethalin followed by bispyribac and hand weeding may provide excellent weed control where bispyribac found effective in killing almost all types of weeds except few grass species. Oxadiargyl and sesbania co-culture with rice performed poorly as these methods also had a low economic return. Although the post-emergence application of bispyribac along with hand weeding had greater weed control and high gross profit, net return was little due to the high cost of labor which also lowered B:C ratio. Nevertheless, hand weeding could be a feasible option for farmers if they have a small area of operation. But for large commercial farms, the only option is to adopt the sequential application of pendimethalin and bispyribac because it allows massive farm mechanization with high net returns and eventually solve the problem of the labor crisis. Integrating a pre-emergence herbicide application with post-emergence appeared to have the best potentiality in controlling DSR weeds.

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Conflict of Interest

There is no conflict of interest among parties involving in this project and between authors synthesizing the paper.

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