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Weed management in direct-seeded rice

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ABSTRACT

Rice (*Oryza sativa*), the staple food of more than half of the population of the world, is an important target to provide food security and livelihoods for millions. Direct seeding of rice (DSR) refers to the process of establishing the crop from seeds sown in the field rather than by transplanting seedling from the nursery. Before the advent of Green revolution and adoption of irrigation, rainfed rice was often broadcasted into moist soil and yields were low, variable and highly prone to weed competition. Weed spectrum and degree of infestation in rice field are often determined by rice ecosystems and establishment methods. Research evidences at different places has shown around 20-100% losses due to weeds such as *Echinochloa* spp., *Leptochloa* spp., *Cyanotis* spp., *Commelina* sp., *Digitaria* spp. and *Alternanthera* sp in DSR. Integrated weed management approach based on the critical period of crop weed competition, involving different direct and indirect control measures, has been developed and widely adopted by farmers to overcome weed problem in DSR in a sustainable way. Stale seed bed combined with herbicide (paraquat/glyphosate) and zero till results in better control. About 53% lower density was recorded due to stale seed bed. Brown manuring of *Sesbania* reduces weed population by 50%. Mulches, crop rotation and rice cultivars like *'Narender 359'* and *'Sarjoo 52'* were found better for Indo- Gangetic plains. Application of penoxsulam 25 g/ha as broad-spectrum, azimsulfuron + metsulfuron-methyl for *Cyperus* spp., pendimethalin at 1.25 kg/ha for *Echinochloa* spp. were found suitable for chemical weed management.Weed-competitive and allelopathic rice varieties, seed priming for increased weed competitiveness, higher seeding density should be considered as a management strategy.

Key words: Direct-seeded rice, Rice production systems, Weeds, Weed management, Weed shifting

Rice (*Oryza sativa* L.) is a member of poaceae family and is relished as staple food by majority of world's population. In India, rice occupied 39.16 million hectares(mha) area with a production of 85.59 million ton and average yield 2.2 t/ha (Anonymous 2013). Among the cereals, rice is the leading crop world wide (Ashraf *et al.* 2006), and more than half of the human race depend on rice for their daily sustenance (Chauhan and Johnson 2011). It is the primary source of income and employment for more than 100 million households in Asia. World's rice demand is projected to increase by 25% from 2001 to 2025 to keep pace with population growth (Maclean *et al.* 2002), and therefore, meeting ever increasing rice demand in a sustainable way with shrinking natural resources is a great challenge.

Transplanting after puddling (a process where soil is compacted to reduce water seepage) has been a major traditional method of rice establishment. Repeated puddling adversely affects soil physical properties by dismantling soil aggregates, reducing permeability in sub-surface layers, and forming hard-pans at shallow depths which make land preparation becomes difficult and requires more energy to achieve proper soil tilth for succeeding crops. Excessive pumping of water for puddling in peak summers in the North-West Indo-Gangetic Plains (IGP) resulted in declining water table. Rice production with transplanting method has been limited by a number of factors such as water scarcity, high input costs, shortage of skilled labor and suboptimal plant population. Rice seedlings are transplanted (TP) by hired skilled labour that resulted in skilled labour shortage throughout the tranplanting period which results into low plant population and eventually low rice yield. To overcome this problem, direct seeding of rice (DSR) seems only viable alternatives in rescuing farmers. Rice yield losses due to uncontrolled weed growth were least in transplanted rice (12%) but otherwise large (*cal.* 85%) where rice had been sown to dry cultivated fields or to puddled soil, rising to 98% in DSR sown without soil tillage. Weed competition reduced multiple rice yield components, and weed biomass in wet-seeded rice was six-fold greater that in rice transplanted into puddled soil and twice as much again in dry-seeded rice sown either after dry tillage or without tillage (Singh *et al.* 2011).

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The risk of greater crop yield losses due to weed competition in DSR systems than in TPR is mainly because of the absence of the seedling size differential between rice and weeds and the absence of the suppressive effect of standing water on weed emergence and growth at crop emergence time. Ramzan (2003) reported yield reduction up to 48, 53 and 74% in transplanted, direct-seeded flooded and direct-seeded aerobic rice, respectively. Aerobic rice is subject to much higher weed pressure with a broader weed spectrum than flood-irrigated rice (Balasubramanian and Hill 2002). Sunil *et al.* (2010) as stated, season-long weed competition in DSR may cause yield reduction up to 80%. Weed problem is sought to be addressed from two basic points of view: weed control and weed management. Control approach only emphasizes on reduction of weed pressure and the management approach, by contrast, focuses on keeping weed infestation at a level compatible with environmentally and economically sustainable production. However, different weed control options are available for rice. Physical control is eco-friendly but tedious and labor-intensive. Other problems include delayed weeding due to unavailability of labor damage to the rice seedlings and mistaken removal of rice seedlings. Biological control by using different bio-agents and mycoherbicides are practiced in irrigated lowland rice, but these may not be effective under aerobic soil conditions. Chemical control, on the contrary, is the most effective, economic and practical way of weed management (Hussain *et al.* 2008, Anwar *et al.* 2012a).

Status of DSR

The yield levels of DSR are comparable to the conventional tillage-transplanted rice (CT-TPR) in many studies. Some reports claim similar or even higher yields of DSR with good management practices. For instance, substantially higher grain yield was recorded in DSR (3.15 t/ha) than TPR (2.99 t/ha), which was attributed to the increased panicle number, higher 1000 kernel weight and lower sterility percentage (Sarkar *et al.* 2003). In addition to higher economic returns, DSR crops are faster and easier to plant, having shorter duration, less labour intensive, consume less water (Bhushan *et al.* 2007), conducive to mechanization (Khade *et al.* 1993), have less methane emissions (Wassmann *et al.* 2004) and hence offer an opportunity for farmers to earn from carbon credits than TPR system (Balasubramanian and Hill 2002). Dry-seeding reduces the overall water demand by reducing losses due to evaporation, leaching, percolation and amount of water needed for land preparation *etc*. (Bouman and Tuong 2001). Direct-seeding also offers the option to resolve edaphic conflicts (between rice and the subsequent non-rice crop) and enhance sustainability of the rice-based cropping system and succeeding winter crops (Farooq *et al.* 2008, Singh *et al.* 2005a) in India.

Rice production system

Rice farming is practiced in several regions and under a wide range of agro-climatic conditions. Over the centuries, naturally occurring selection pressure such as submergence, drought, and biotic stresses has widely diversified the rice ecosystem (FAO 2004). Traditionally, rice has been cultivated in flooded conditions mostly for irrigation and effective weed control (Bouman 2003). But due to shortage water, flood irrigated rice has been replaced by different less labor dependent and water saving production systems. Khush (1997) has categorized rice land ecosystems into four types. According to FAO (2007), irrigated, rainfed lowland, upland and deep water rice area have been estimated as 56.9, 30.9, 9.4 and 2.8% worldwide. In Asia, 58.6% of rice growing area is under irrigated, 32.1% under rainfed lowland, 6.7% under upland and 2.6% under deep water cultivation system. Thus, among the four rice ecosystems, irrigated rice is the main system, in terms of both area coverage and production. Irrigated rice occupies more than 50% of world rice area supplying more than 75% of global rice demand (FAO 2007). Unfortunately, this most important rice ecosystem is being increasingly endangered due to water scarcity threatening the world food security.

The promising rice technological options and crop and resource management practices designed to improve input use efficiency, save input costs and reduce the environmental footprint of irrigated rice production include site-specific nutrient management , integrated pest management and water-saving technologies such as alternate wetting and drying aerobic rice systems (FAO 2014-15).

Direct-seeding of rice refers to the process of establishing the crop from seeds sown in the field rather than by transplanting seedlings from the nursery (Farooq *et al.* 2011). Direct-seeding avoids three basic operations, namely, puddling (a process where soil is compacted to reduce water seepage), transplanting and maintaining standing water. There are three principal methods of (Table 1) establishing the direct-seeded rice (DSR): dry seeding (sowing dry seeds into dry soil), wet seeding (sowing pre - germinated seeds on wet puddle soils) and water seeding (seeds sown into standing water). Wet-DSR is primarily done under labour shortage situation, and is currently practiced in Malaysia, Thailand, Vietnam, Philippines, and Sri Lanka (Pandey and Velasco 2002, Weerakoon *et al.* 2011)

Major weed flora in DSR

Before the advent of the green revolution and adoption of irrigation, rain fed rice was often used to be broadcasted into moist soil (Pandey and Velasco 2002) and yields were low, variable, and highly prone to weed competition, as is still experienced today, particularly in upland rice (Roder *et al.* 2001). There is now evidence that water scarcity prevails in rice growing areas, and societal demands for water from the urban and commercial sectors will continue to increase. Direct-seeding of rice, in place of transplanting, provides opportunities for water savings but at the expense of the absence of the suppressive effective of standing water on weed growth. Hence, the DSR crop faces severe challenges from weeds, and effective weed management is essential for cropping of DSR.

Weed infestation is one of the major biotic constraints in rice production. Rice community is infested with diverse type of weed flora colonized by aquatic, semi-aquatic and terrestrial weeds, grown under diverse agro-climatic conditions, different cropping sequence, tillage and irrigation regimes. About 350 species have been reported as weeds of rice, of which grasses are ranked as first posing serious problem followed by sedges and broad-leaf weeds causing major losses to rice production worldwide. The predominant weed associated with DSR in Asia has been presented (Table 1)

Community composition of weeds varies according to crop establishment methods, cultural methods, crop rotation, water and soil management, location, weed control measures, climatic conditions, and inherent weed flora in the area. *Echinochloa colona* and *E. crus-galli* are the most serious weeds affecting DSR. The density of these weeds in DSR depends upon moisture condition in the field. *E. colona* requires less water, so it is more abundant in DSR. *Cyperus rotundus* and *Cynodon dactylon* may be major problems in poorly managed fields or where un-decomposed farm yard manure has been applied. The other weeds of major concern in DSR are *Paspalum* spp., *Ischaemum rugosum*, *Leptochloa chinensis*, *Digitaria sanguinalis*, *Dactyloct-enium aegyptium*, C*ommelina* spp., *Caesulia axillaris*, *Cyperus iria*, *Fimbristylis miliacea* and *Cyperus difformis.*

Table 1. Major weed species in direct-seeded rice

Scientific Name	Common Name	Family
Grasses		
Echinochloa colona	Wild rice	Poaceae
Echinochloa crus-galli	Barnyard grass	Poaceae
Eleusine indica	Goosegrass	Poaceae
Leptochloa chinensis	Sprangletop	Poaceae
Digitaria sanguinalis	Large crab grass	Poaceae
Brachiaria ramosa	Signal grass	Poaceae
Cynodon dactylon	Bermuda grass	Poaceae
Dactylotenium aegyptium	Crow foot grass	Poaceae
Broad-leaf weeds		
Alternanthera sessilis	*Khaki weed*	Amarathaceae
Ammania baccifera	*Redstem*	Lythraceae
Caesulia axillaris	Pink node flower	Asteraceae
Celosia argentia	Quail grass	Amarathance
Cleome viscosa	Cleome	Capparaceae
Commelina benghalensis	Wandering jaw	Commelinaceae
Commelina communis	Dayflower	Commelinaceae
Cyanotis axillaris	Creeping cradle	Commelinaceae
Digera arvensis	Digera kondra	Amarathaceae
Sedges		
Fimbristylis miliacea	Globefingerush	Cyperaceae
Cyperus difformis	Small flower umbrella sedge	Cyperaceae
C. iria	Flat sedge	Cyperaceae
C. rotundus	Purple nut sedge	Cyperaceae

In DSR during the first 30 days after sowing, non-grassy weeds (broad-leaf) dominated the grassy weeds and sedges, contributing more than 62% of the total weed population where *Trianthema monogyna* alone contributed more than 50 and 60% at 150 and 30 days after sowing, respectively (Table 2). At later stages, grasses dominated over non-grasses and sedges, contributing more than 90% of the total weed population at 75 DAS, at which *E. colona* alone contributed more than 80% of the total weed population at 60 DAS and beyond (Singh 2008).

Studies conducted at Pantnagar in station trail and on farm trails indicated that *C. rotundus* may pose a severe threat to direct-seeded rice system where regular flooding is absent (Singh 2008).

Losses caused due to weeds in direct-seeded rice

Weeds in DSR adversely affect yield, quality and cost of production as a result of competition for various growth factors. Extent of loss may vary depending upon cultural methods, rice cultivars, rice ecosystems, weed species association, their density and duration of competition. The greatest loss caused by the weeds, resulted from their competition with crop for growth factors, *viz*. nutrients, soil moisture, light, space, *etc* (Walia 2006). *Trianthema monogyn*a was found to grow faster than other weeds during

Table 2. Percentage composition of grassy weeds, non-grassy weeds, and sedges and their contribution (%) to dry matter production of weeds (g/m^2) at different stages (average of three crop season in unweeded plots)

Stage (DAS)	Grassy weeds		Non-grassy weeds		Sedges	
	Population	Dry matter	Population	Dry matter	Population	Dry matter
15	30.0	25.2	60.0	72.6	10.0	2.2
30	29.2	11.0	62.6	88.4	8.2	0.6
45	54.0	88.9	15.4	8.7	30.6	2.4
60	85.2	98.7	0.0	0.0	14.8	1.3
75	90.8	99.5	0.0	0.0	9.2	0.5

(Source: Singh 2008) *DAS = days after sowing

early stage due to shorter life cycle and contributed much more to the competition as compared to other weeds (Singh 2008). Globally, actual yield losses due to pests have been estimated ~ 40%, of which weeds caused the highest loss (32%) (Rao *et al.* 2007). Yield losses are largely dependent on the season, weed density, weed species, rice cultivars, growth rate, management practices and rice ecosystem. Azmi and Baki (1995) estimated that the yield loss caused by grasses (mainly *E. crus-galli*), broad-leaved weeds and sedges was 41, 28 and 10%, respectively. Weedy rice (*Oryza sativa f. spontanea*), also known as red rice, has emerged as a serious threat. It is highly competitive and causes severe rice yield losses ranging from 15% to 100% (Farooq *et al.* 2009). Weedy rice also reduces milling quality if it gets mixed with rice seeds during harvesting (Ottis *et al.* 2005). Therefore, a systematic, efficient and effective weed management depends on timing and method of land preparation, effectiveness of herbicides, relative to the dominant weed species and soil conditions at the time of application, effect of weather on weeds and effect of combining herbicides and manual weed control. In 2004, yield loss equivalent to RM90 million was estimated due to weedy rice infestation in direct-seeded rice in Malaysia (Azmi and Rezaul 2008). However, water regimes in rice fields might determine the extent of yield loss due to weed competition. On average, estimated losses from weeds in rice are around 10% of total grain yield; however, can be in the range of 30 to 90%, reduces grain quality and enhances the cost of production (Rao *et al.* 2007). In Bangladesh, rice yield losses due to weeds were estimated by 70-80% in *Au*s rice (early summer), 30-40% in transplanted *Aman* rice (late summer) and 22-36% in *Boro* rice (winter rice) (BRRI 2006).

Yield reduction due to weeds is more critical in direct-seeded rice than in transplanted rice (Karim *et al.* 2004). The competitive advantage of TPR over DSR is due to the use of 4-5 weeks old seedlings (20-30 cm tall) in TPR and also that the weeds emerging after rice transplanting are controlled by flooding after transplanting in TPR compared to DSR. In dry-seeded aerobic rice, relative yield loss caused by weeds is as high as 50-91% (Rao *et al.* 2007), while in TPR, yield loss has been estimated to be only 13% (Azmi 1992). Among the different establishment systems, yield losses are the slightly lesser in DSR (6.10 t/ha) as compared to wet-seeded rice (6.75 t/ha) and TPR (6.35 t/ha) under irrigated ecosystem. (Singh *et al.* 2006a). Dhyani *et al.* 2010 recorded lowest density and dry weight of *E.colona* in TPR as compared to DSR. Season-long weed competition in direct- seeded aerobic rice may cause yield reduction up to 80% (Sunil *et al.* 2010). In extreme cases, weed infestation may cause complete failure of aerobic rice (Jayadeva *et al.* 2011). Thus direct-seeded aerobic rice is highly vulnerable to weeds compared with other rice ecosystems (Anwar *et al.* 2011).

Weed shift in DSR

Yield losses from weeds and the effectiveness of control measures depend largely upon the weed species present. Factors,which affect the composition of the weed flora include landscape position, water control, soil fertility, season, rotations and herbicide use (Moody 1996). A shift in weed populations with changing cultivation practices is thus a predictable consequence of intensification (Mortimer 1990). Direct-seeding has replaced transplanting in Asia, the annual grasses *Echinochloa colona* and *Leptochloa chinensis* have succeeded the previously dominant *Monochoria vaginalis* and *Ludwigia hyssopifolia* (Ho and Itoh 1991).

Continuous use of herbicides for the control of annual grasses shifted the dominant species from grasses to broad-leaf weeds and sedges and from annuals to perennials. The advent of direct-seeding and insufficient water supply are perceived as factors responsible for the shift in weed species dominance and diversity in rice ecosystems. Moreover, changes from traditional transplanting to direct-seeding culture (1980's onward) resulted in drastic changes of weed flora from easy- to difficult- to-control weeds. These ecological responses in the weed flora are largely are result of habitat changes at the time of germination and establishment, associated with the absence of standing water. Extensive use of herbicides has been reported to promote shifts in the weed population (Azmi and Baki 2002). In India continuous use of grass killers such as butachlor in rice has resulted in a shift of weed flora to sedges as *C. iria*, *Scripus* spp., and *Fimbristylis* spp. (AICRP-WC-2002-03). Mortimer and Johnson 2008 during the study at Pantnagar confirmed that changing from transplanting to direct-seeding caused marked changes in the weed flora in the rice-wheat system. With direct-seeding of rice there was a rapid increase in annual grasses, *Echinocloa colona, E.crus-galli, Leptochloa chinensis*: perennial sedge *Cyperus rotundus* and certain broad-leaf weeds such as *Caesulia axillaris*. Research on farmers field showed that direct-seeding of rice is accompanied by a rapid shift in weed flora with an increase in abundance of E.*colona, E. crusgalli, Ischaemum rugosum* and *Leptochloa chinensis* and on more freely draining soil *C.rotundus* (Singh *et al.* 2006). Singh *et al.* (2013), reported that replacing transplanted rice to direct seeding rice resulted an increase in weed growth and also shift in the relative abundance of particular species. Direct seeded rice is accompanied by a rapid shift in weed flora with an increase in *E.colona, E .crusgalli* and *Ischaemum rugosum*.

Studies comparing crop establishment and weed management options at Pantnagar, over a 4-year period have shown that changing from TPR to DSR resulted in marked changes in weed populations in the rice-wheat system. In general, with diret-seeding, three annual grasses, *Echinochloa crus-galli, E. colona*, and *Leptochloa chinensis*, the perennial sedge *Cyperus rotundus*, and certain broad-leaf weeds such as *Commelina diffusa* and *Caesulia axillaris* increased (Fig. 1).

Weed management strategies

Multiple setbacks to weeds seem to be the best strategy to control weeds in DSR. Some of the strategies are discussed below and these should be used in conjunction rather than in isolation. Many researchers working on weed management in DSR opined that herbicide may be considered to be a viable alternative/supplement to hand weeding (Chauhan and Johnson 2011, Anwar *et al.* 2012). The other option left is cultural weed control through adoption of different agronomic practices including tillage (Rao *et al.* 2007), competitive cultivar (Zhao *et al.* 2006a), seeding density (Anwar *et al.* 2011), water

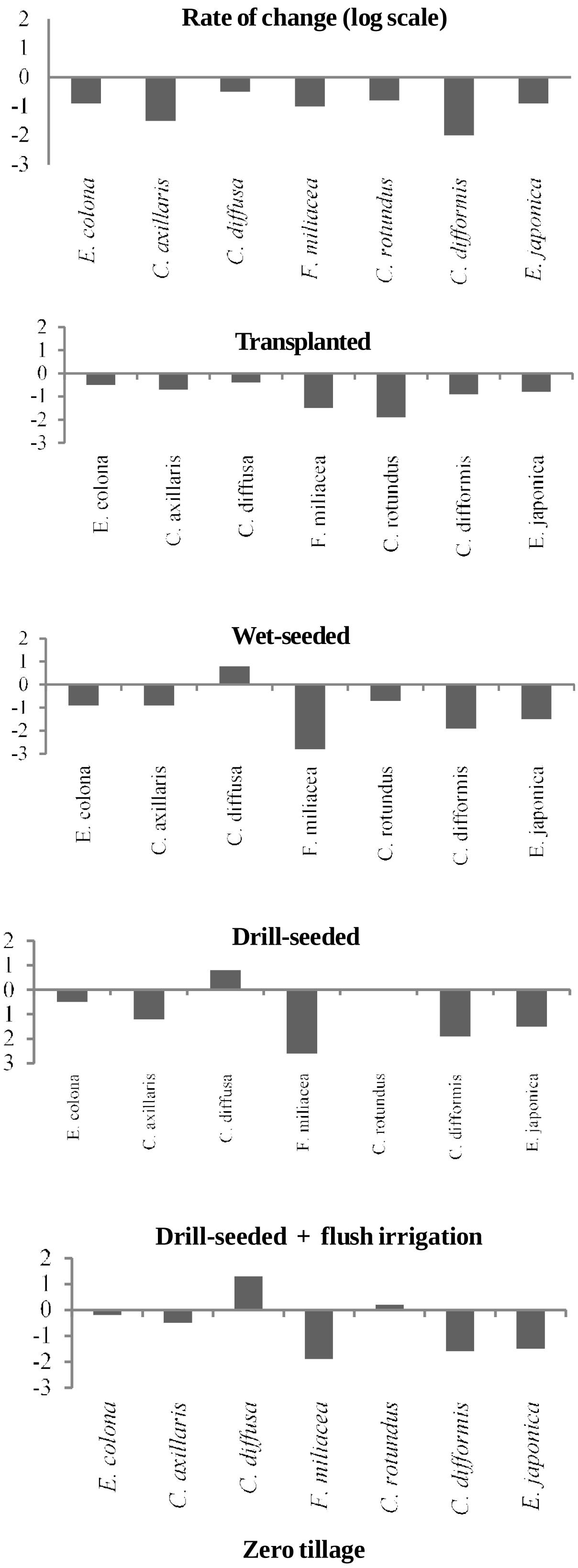

Fig. 1. Changes in abundance (mean density at 28 DAS/ DAT) of weeds according to rice establishment method for species recorded in 2002. Data are the logarithm of the ratio of densities in 2004 to 2002, Pantnagar (Singh *et al.* 2008)

management (Rao *et al.* 2007), fertilizer management (Blackshaw *et al.* 2005), seed invigoration (Ghiyasi *et al.* 2008), mulching (Singh *et al.* 2007a). Although these agronomic tools help to increase competitive ability of crop against weeds and at the same time are eco-friendly and economic, but may not provide acceptable level of weed control, especially under aerobic soil conditions, where weed pressure is very high. A single weed control approach may not be able to keep weeds below the threshold level of economic damage, and may results in shift in the weed flora, resistance development and environmental hazards. Therefore, adoption of diverse technology is essential for weed management because weed communities are highly responsive to management practices. Besides, farmers are now becoming increasingly interested in more inclusive weed management strategy to reduce herbicide dependence (Blackshaw *et al.* 2005).Therefore, while addressing environmental concern, all the methods that are ecologically and economically justifiable should be integrated in a comprehensive way, known as integrated weed management (IWM). The IWM involves the selection, integration, and implementation of effective weed control means with due consideration of economics, environmental, and sociological consequences. Concern over long-term efficacy of herbicide dependent weed management has reinforced the need for IWM. A substantial impact of IWM on rice farming has been documented by many researchers (Sunil *et al.* 2010, Jayadeva *et al.* 2011). Therefore, there is need to integrate herbicide use with other management strategies to achieve effective, long term and sustainable weed control in direct seeded rice systems. This review aims to sum up earlier work on different weed management approaches in DSR and discuss future research needs and strategies to continue to manage weeds effectively and economically, in a sustainable manner.

Preventive measures

Sowing of clean seed is perhaps the most important weed management technique in any crops. Rice seed contaminated with weeds is one of the major causes of weed infestation, especially in DSR. Rice seeds infested with weed seeds may introduce problematic weed species to a new field and increase the seed numbers in the soil weed seed bank. In many countries, for example, weedy rice or red rice spreads through the distribution of contaminated rice seeds to farmers and now this weed has become a menace because of the non availability of selective herbicides to control it. Mai *et al.* (1998) reported on average 466 weed seeds/kg rice seeds including 314 weedy rice seeds in Vietnam, which is 47 fold higher than permitted national purity level. In addition to clean crop seed, the machinery used for tillage, sowing, harvesting or threshing operations should also be cleaned before moving it from one field to another. Preventing weeds from entering an area may be easier than trying to control them once.

Cultural control

Cultural approaches play significant role to determine the competitiveness of a crop with weeds for above ground and below ground resources and hence might influence weed management (Grichar *et al.* 2004). Most cultural practices can be regarded as a means of weed suppression and an increase in their efficiency would contribute to better weed control. Moreover cultural control is also considered to be eco-friendly and when combined with herbicides or other methods can result in better weed management.

Stale seed bed: The stale seed bed technique is an important cultural practice that can be used before any crop to reduce the weed seed bank. In this technique, after pre-sowing irrigation, fields are left as such and weeds are allowed to germinate and thereafter are killed through cultivation or with the use of non-selective herbicide (e.g., paraquat or glyphosate) application or shallow tillage. This technique is quite effective in DSR, especially for controlling weeds such as *C. rotundus,* weedy rice, and volunteer rice seedlings. Herbicides may destroy weeds without disturbing the soil, which would be advantageous and hence reducing the possibilities of bringing new seeds to the upper soil surface. The rice seeds should be sown with minimum soil disturbance after destroying the emerged weeds. The use of zero-till-ferti-seed drills may be useful to serve this purpose. Singh *et al*. 2009 reported 53% lower density in Dry- DSR after a stale seed bed than without this practice. Stale seedbed combined with herbicide (paraquat) and zero-till results in better weed control because of low seed dormancy of weeds and their inability to emerge from a depth >1 cm (Chauhan and Johnson 2010). The success of stale seed bed de-pends on several factors: (a):- method of seed bed preparation (b):- method of killing emergence weed (c):- weed species (d):- duration of stale seed bed and (e):- environmental conditions.

Tillage: Tillage is an important cultural practice to reduce the incidence of perennial weeds. Dry-seeded rice can be sown under zero till or reduced till conditions or thorough land preparation. The importance of thorough land preparation to minimize weed pressure is well recognized. Tillage can affect weed community through the changes in weed seed distribution in the soil. Primary tillage can reduce annual weed populations, especially when planting is delayed to allow weed seeds to emerge before final tillage. While shallow tillage before crop emergence and post plant tillage after crop establishment help remove annual weeds and inhibit the growth of perennial weeds. On the other hand, zero tillage favors weed infestation. Conservation tillage has been criticized particularly in relation to lower yields and perennial weed problems which results in an increase in herbicide application (Singh *et al*. 2011). Zero tillage DSR had more equivalent yield than DSR CT. Presence of crop residue in tillage practices increases weed suppression and tillage in darkness can delay and reduce the emergence of certain weed species.

The rice yield was statistically at par in case of zero tillage (ZT) when compared with the conventional tillage (CT) system in DSR (Bhattacharayya *et al.* 2006). It was further reported that ZT may be adopted as resource conservation technology (RCT) and producing good crop yield. Another study reported that DSR with conventional seeding (in the prepared field) or rotavator (RT) seeding was better than ZT seeding. However, soil quality parameters (*viz.* soil organic carbon (SOC) concentration, bulk density and moisture content) were significantly better under conservation tillage (ZT and RT) than CT (Bazaya *et al.* 2009). CT recorded significantly higher yield than ZT (Bhatacharayya *et al.* 2006). Another study recorded that the direct-seeded ZT gave at par yield as compared with transplanted (TP) rice (Singh *et al.* 2008). ZT rice after spray of glyphosate 0.5 kg/ha gave significantly higher yield over the other methods of establishment.

Brown manuring (*Sesbania* co-culture): "Brown manuring" practice involves seeding of rice and *Sesbania* crops together and killing the *Sesbania* crop 25-30 days after sowing (DAS) by application of 2,4-D-ester at 0.40-0.50 kg/ha. This will also help in meeting early N requirement of the crops and avoid early nitrogen and moisture stress (CIMMYT 2010, Gurjeet *et al.* 2013). Methane gas emission and global warming potential was maximum under conventional- TPR and emission of N_2O was maximum under DSR crop with conservation practice of brown manuring as the addition of organic matter to soil increased the decomposition rate, which resulted in higher emission of GHGs (Bhatia *et al.* 2011).

Water management: In rice cropping, water constitutes a powerful selective agent for weed management (Mortimer and Hill 1999). Water is the "best herbicide". Every weed species has an optimum soil moisture level, below or above which its growth is hampered, and therefore time, depth and duration of flooding could play an important role in suppressing weeds. Water depth can be used to control many weeds, but some species are relatively unaffected by water depth. Good water management together with chemical weed control offers an unusual opportunity for conserving moisture and lowering the cost of rice production (Rao *et al*. 2007). The importance of water management for controlling weeds in rice is well-known but water management is yet to achieve its full potential.

The effect of rice crop establishment methods on infiltration rate was recorded at PDCSR, Modipuram (Uttar Pradesh) during 2004. The infiltration rates of the three transplanting methods (irrespective of puddling) were almost the same (31-34 mm/day). The infiltration rate of direct-seeded plots in a dry bed (75 mm/day) was higher than in drum-seeded plots in a wet bed (65 mm/day).

If germplasms are developed for rice, which cause very rapid growth than water level can be increased initially to control weeds. The extent to which genes that ensure rapid establishment and submergence tolerance can be exploited for germplasm adapted for direct seeding remains a pressing research issue.

Fertilizer management: Fertilization affects weed growth in rice fields. Manipulation of crop fertilization is a promising approach to reduce weed infestation and may contr-ibute to long-term weed management (Blackshaw *et al*. 2004). Fertilizer management should be aimed at maximizing nutrient uptake by crop and minimizing nutrient availability to weeds. Nitrogen fertilizer has been reported to break weed seed dormancy and influence weed densities. The time of nitrogen application also influences weed growth. Many weed species consume high amount of N and; thus, reduces N availability for crops. The proper mana-gement of N in DSR reduces the weed competition, and hence should be applied as per the requirement of the crop. The application of excess amount of N fertilizer, on the other hand, encourages weed growth and reduces yield. Recently, Mahajan and Timsina (2011) reported that when weeds were controlled, rice crop responded to higher amount of N application but under weedy and partially-weedy conditions, grain yield reduced drastically with higher amount of N fertilization. With inadequate weed control, it is best not to apply N or to apply N at low amounts.

Weed-competitive cultivar: Rice cultivar with strong weed competitiveness is deemed to be a low-cost safe tool for weed management (Gibson and Fischer 2004). Short stature, early maturing, erect rice cultivars are less competitive with weeds than cultivars that are tall and have fast and vigorus early vegetative growth, a vigorus root system, high tillering and drooping leaves. It has been observed that early maturing rice cultivars and rice hybrids also have a smothering effect on weeds due to improved vigour and having the tendency of early canopy cover (Mahajan *et al.* 2011). Competitive rice cultivar effectively supp-ressed the infestation of *Echinochloa* spp. and helped reduce herbicide dependency (Gibson *et al.* 2001).

At present, no varieties are available that are targeted for alternate tillage and establishment methods, especially in unpuddled or ZT soil conditions with direct-seeding (Dry-DSR) in Asia (Fukai 2002, Watanabe *et al.* 1997). Direct dry-seeded rice requires specially bred cultivars having good mechanical strength in the coleoptiles to facilitate early emergence of the seedlings under crust conditions (generally formed after light rains), early seedling vigour for weed competitiveness (Jannink *et al.* 2000, Zhao *et al.* 2006a), efficient root system for anchorage and to tap soil moisture from lower layers in peak evaporative demands (Clark *et al.* 2000. Pantuwan *et al.* 2002) and yield stability over planting times are desirable traits for DSR.

Seeding rate: High seeding rates are used in DSR systems. Farmers used high seed rate to compensate for poor seed quality and poor crop emergence as they use their own stored seeds and compensate for losses due to rodents, birds, insects *etc*. In addition, the use of high seed rates can also help in suppressing weed growth. Low plant density and high gaps encourage the growth of weeds, and in many cultivars, result in less uniform ripening and poor grain quality. On the other hand, very high plant stand should be avoided because it tends to have less productive tillers, increases lodging, prevents the full benefit of nitrogen application, and increases the chances of rat damage. A study was conducted in the Philippines and India in 2008 and 2009 to assess the relations of seeding rate (15-125 kg/ha) of hybrid and inbred varieties to crop and weed growth in aerobic rice. Plant densities, tillers and biomass of rice increased linearly with increased in seeding rates under both weedy and weed free environments. Weed biomass decreased linearly with increasing seed rate from 15 to 125 kg/ha. Panicles and grain yield of rice in competition with weeds increased in a quadratic relation with increased seeding rates at both locations: however, the response was flat in the weed free plots. A quadratic model predicted that seeding rates of 48-80 kg/ha for the inbred varieties and 47-67 kg/ha for the hybrid varieties were needed to achieve maximum grain yield when grown in the absence of weeds, while rates of 95-125 kg seed/ha for the inbred varieties and 83-92 kg seed/ha for the hybrid varieties were needed to achieve maximum yields in competition with weeds. On the basis of these results, seeding rates > 80 kg/ha are advis-able where there are risks of severe weed comp-etition. Such high seeding rates may be prohibitive when using expensive seed, and maximum yields are not the only consideration for developing recommendations for optimizing economic returns for farmers. (Chauhan *et al.* 2011). Higher seeding rates would be beneficial if no weed control is planned or if only partial weed control is expected. However, it is not necessary to use high seeding rates to suppress weeds in DSR if effective herbicides are used.

Crop rotation: Crop rotation can be used to minimize crop damage from weeds. Rotating crops having dissimilar life cycles or cultural conditions (so as to break the cycles of the weeds) is among the, most effective of all weed control methods. Intensive cropping systems can increase the competitive ability of the crops, thereby reducing the weed pressure. The direct-seeded CT plots had similar grain yield as the direct-seeded ZT plots of rice and wheat after 4 years of cropping (Bhattacharyya *et al.*, 2008). However, the ZT practice had lower cultivation costs and crops under ZT could be sown earlier than CT (Singh *et al.* 2002). However, the significantly same grain, straw and biological yield was recorded with ZT in standing stubbles after removal of loose straw, CT with and without mulching (Singh 2010). Sharma *et al.* (1995) observed that the higher total productivity of 9.3 t/ha was recorded under direct-seeded, puddled condition, followed by transplanting (9.1 t/ha) and direct-seeded, dry condition (8.99 t/ha). Owing to substantial saving of labour under direct-seeded, puddle condition higher net returns of ₹14741/ha was obtained compared with ₹ 498/ha under direct-seeded, dry condition and ₹12981/ha under TPR.

In North India, rice wheat is a dominant system and similar type of crops the rotation also allows similar weeds to flourish. It is difficult however, to replace crops of rotation due to food habits, market, support price etc. It is possible however to diversify this system especially with technologies such as DSR and zero tilled wheat. These technologies give additional one month in between rice and wheat crops. Growing short duration potato, vegetable or legumes in rice-wheat system may ameliorate soil fertility and break the cycle of weed and disease complex as against continuous rice-wheat system over extended period. Weed problem in rice has been observed to be reduced by planting cowpea during dry season, rather than keeping the field fallow. Planting mungbean in dry season in Northern India also reduced weed growth and weeding time and increased herbicide performance (Mahajan *et al*. 2012). This practice is more effective in suppressing weeds, therefore if combined with pre-emergence application of pendimethalin, its performance in suppressing weeds increases.

Residue management and co culture: Crop residue present on soil surface not only improves soil and moisture conservation but can also influence weed seedling emergence and weed growth. However, the response of weeds to residue depends on many factors, including the quantity and position of weed seeds relative to the residue, and the biology of the weed species. In some areas, where time is sufficient between two crops, legume crops such as *Sesbania* and mungbean can be used to reduce the weed population. These crops are killed by using nonselective herbicides and their residue may not only help in suppressing weed emergence but also add fertility to the soil. *Sesbania* co-culture technology can reduce the weed population by nearly half without any adverse effect on rice yield (Dhyani *et al*. 2007). It involves seeding rice and *Sesbania* crops together and then killing *Sesbania* with 2, 4-D ester about 25-30 DAS. *Sesbania* grows rapidly and suppresses weed. This practice is found more effective in suppressing weeds therefore if combined with pre-emergence application of pendimethalin, its performance in suppressing weeds increases. In yet another study (Singh and Singh 2007), *Sesbania* co-culture reduced broad-leaf and grass weed density by 76-83% and 20-33%, respectively, and total weed biomass by 37-80% compared with sole rice crop. *Sesbania* knocked down by the application 2, 4-D 0.5 kg/ha at 30 DAS was found more effective towards the density of weeds than application of pretilachlor, butachlor and fenoxaprop in DSR (Singh *et al*. 2012).

Physical control

Physical control is done manually or mechanically. Crops show varying sensitivity to disturbance, and monocotyledons like cereals are less sensitive than dicotyledons (Rasmussen and Accard 1995), therefore, mechanical weeding is feasible in rice. Harrowing has been found effective in direct-seeded rice, especially when the crop plants are larger than weeds to escape damage (Rasmussen and Accard 1995). Hand weeding is very easy and environment-friendly but tedious and highly labor intensive, and; thus is not an economically viable option for the farmers. It has been estimated that 150 -200-labor-day/ha are required to keep rice crop free of weeds (Roder 2001). Moreover, morphological similarity between grassy weeds and rice seedlings makes hand weeding difficult at early stages of growth. The other problems with manual weeding include quite often weeding is delayed or even cancelled due to unavailability and/or high wages of labor and damage to the rice seedlings.

Biological control

Biological weed control by using different herbivorous bio-agents such as fish, tadpoles, shrimps ducks and pigs are used to control weeds in irrigated lowland rice in a few countries but these cannot be used in aerobic rice, where there is no standing water. Weed control by mycoherbicides are now being studied to reduce herbicide dependency. The most promising fungi for biocontrol of barnyardgrass are *Exserohilum monocerus* and *Cocholiobolus lunatas*. *Setosphaeria* sp. *C. rostrata* were also found to effectively control *Leptochloa chinensis* without causing any damage to rice plant (Thi *et al*. 1999). However, scope of using mycoherbicides is also limited in controlling weeds in direct-seeded aerobic rice because such fungal pathogen requires flooded conditions. Moreover, biological control strategy is not something on which one can solely depend to control weeds especially in DSR where weed pressure is tremendous. Biological strategy should be used in conjunction with herbicides. However this is an interesting area of research where efforts can be made to develop biological control strategy which is compatible with other methods.

Chemical control

Manual and mechanical methods used to control weeds in rice could not find much place among farmers because of the high labour cost, scaricity of labour during the critical period of weed competition, and unfavourable weather at weeding time. Under such situation, herbicides have been tremendous contributor to agriculture. In large scale rice farming, herbicide based weed management has become the smartest and most viable option due to scarcity and high wages of labor (Anwar *et al*. 2012). Despite some undesirable side-effects, no viable alternative is presently available to shift the chemical dependence for weed management in rice. Many researchers working on weed management in DSR opined that herbicide may be considered to be a viable alternative/ supplement to hand weeding (Chauhan and Johnson 2011, Anwar *et al.* 2012).

Application of penoxsulam at 20, 22.5 and 25 g/ha have better control over the density of grasses and broad-leaf weeds in DSR (Singh *et al.* 2012). Singh *et al.* (2010) found effective control over the density of *C. rotundus* with the application of azimsulfuron + MSMetsulfuron-methyl. Lowest population of *E. colona* was recorded with application of pendimethalin at 2.0 kg while of *C. axillaris* was with combined application of bentazone with pendamethalin (Singh *et al.* 2005). Therefore, it is must to use herbicide judiciously (Anwar *et al.* 2012). Other herbicides that are found effective in DSR are pyrazosulfuron and oxadiragyl as pre-emergence and azimsulfuron, penoxsulam, cyhalopfop-butyl, and ethoxysulfuron as post-emergence (Rao *et al.* 2007). It must never be overlooked that all pesticides are toxic; they must be handled safely so as to reduce or avoid excessive and costly wastes, environmental concerns, crop damage, damage to adjacent crops by spray drift, injury to the applicator, excessive contamination and residues, and injury to beneficial organisms. It is advisable to rotate the herbicide combination in each year for delaying the development of herbicide resistance in weeds.

Integrated weed management

Weed-rice ecological relationships are never static. The continuous adoption of any particular rice production practice causes a shift in dominance and distribution of rice weeds. In the formation of weed management programs, the type of rice culture, cultivars grown, tillage, crop establishment methods, planting geometry, fertilizer application and water management need to be systematically manipulated so as to create favourable conditions for crop growth, but unfavourable for weed survival. Manual and mechanical weeding in DSR should be used only in

Table 3. Recommendations of herbicides for weed management in direct dry seeded rice

Herbicide (Trade name)	Dose (g/ha)	Product (g or ml/ha)	Stages of Application	Weed control
Pre-emergence herbicide				
Pendimethalin 30 EC (Stomp, Pendistar)	1000-1500	3000-4500 light to heavy soil	0-3 DAS	Controls the annual grasses and some BLWs. Could be used for weed control in wet- seeded nursery as well.
Pretilachlor 30.7% EW (Rifit, Erage-N)	450-600	1500-2000	0-3DAS	Very effective in control of grassy weeds under puddle condition. Require wet soil moisture for few days for effective weed control
Oxadiagryl 6 EC (Raft)	90	1500	0-3 DAS	Gives excellent controls of grasses and some sedge. Control of BLWs is not satisfactory
Oxyflurofen 23.5 EC (Goal and Zargon)	150-240	650-1000	0-6 DAS	Control many annual grasses, some BLWs and sedges
Anilofos 30EC (Arozin, Aniloguard)	400	1200	3-5DAS	Control many annual grasses and some BLWs. Apply on saturated soil and do not flood next 2-3 days
Oxadiazon 25EC (Ronstar)	500-750	2000-3000	Pre-em. or early post emergence	Control broad spectrum of weeds. Do not disturb the soil surface after application
Post-emergence herbicide				
Cyhalofop-butyl 10 EC (Clincher, Wrap-up)	75-80	750-800	15-20 DAS	Excellent Control of annual grasses particularly barnyard grass and *Leptochloa*
Bispyribac-sodium 10SC (Nominee gold, Adora)	20	200	15-20 DAS	Controls annual grasses and some BLWs and sedges.
Penoxsulam 24SC (Grainite)	22.5	93.7	15-20 DAS	Controls the annual grasses and some BLWs and sedges.
Chlorimuron-ethyl + Metsulfuron-methyl 20 WP (Almix)	4	20	15-20 DAS	Control broad spectrum of weeds including annual BLWs and grasses.
Ethoxysulfuron 15%WDG	12.5-15	83.3-100	15-20 DAS	Give effective control of broad-leaved and sedges.
Azimsulfuron 50WG (Segment)	35	70	20 DAS	Controls annual grasses and some BLWs and sedges
2,4-D 38 EC, 34 EF, 80 WP (Weed kill Weedmar, Knockweed etc.)	750-1000	2250-3000	20-25 DAS	Apply 20-25 days where Sedges and BLWs weeds are dominant. Drain before application of herbicide reflood again for few days. Good against water hyacinth and *Monochoria*.
Pyrazosulfuron-ethyl 10WP (Saathi)	25	200	20-25 DAS	Give effective control of broad-leaved and sedges.
Fenoxaprop-p-ethyl 6.7EC (Rice Star)	56.6-60.38	812.5-875	25-30 DAS	Excellent Control of annual grasses. May be applied as a follow up application with all pre-em. herbicide
Fenoxaprop-p-ethyl 9.3EC (Whip supar)	60-70	800-1000	25-30 DAS	

Table 4. Effect of herbicide combinations on weeds and yield of dry-seeded irrigated rice

Treatment	Dose (g/ha)	Weed density (no. /m^2) at 60 DAS			Grain yield (t/ha)
		Echinochloa spp.	*C. axillaris*	Annual sedges	
Pendimethalin	1000	1.4	108.0	181.4	3.64
Pendimethalin followed by 2,4-D	1000 *fb* 500	0.0	0.0	0.0	5.91
Pendimethalin followed by almix	1000 *fb* 4	4.0	0.0	0.0	6.06
Weedy	-	94.5	2.7	170.7	1.01
Weed free	-	-	-	-	6.32
LSD (P=0.05)	-	-	-	-	0.51

conjunction with other cultural and chemical methods to minimize labour requirements where appropriate.

None of the control measures in single can provide acceptable levels of weed control, and therefore, if various components are integrated in a logical sequence, considerable advances in weed management can be accomplished. Various agronomic tools have been evaluated for their potentiality in managing weeds (Liebman *et al.* 2001). But, all the agronomic tools may not work perfectly with every crop or weed species (Blackshaw *et al.* 2005). Integration of higher seed rate and spring-applied fertilizer in conjunction with limited herbicide use managed weeds efficiently and maintained high yields (Blackshaw *et al.* 2005). Adoption of IWM approach for sustainable rice production has been advocated by many researchers (Azmi and Baki 2002, Sunil *et al.* 2010, Jayadeva *et al.* 2011). Singh (2008) recorded that the sequential application of pre-emergence herbicides such as pendimethalin, in dry-seeded rice or early post-emergence application of anilofos/thiobencarb for the control of annual grasses in wet-seeded rice and post-emergence application of 2,4-D against sedges and non-grassy weeds in wet and dry-seeded rice may be a better option than the use of one herbicide. Some of the combinations or their sequential application may widen the weed control spectrum with better efficacy. Follow up application of 2,4-D and Almix (a ready mixture of chlorimuron-methyl and metsulfuron-methyl) as post-emergence over preemergence application of pendimethalin in DSR provided effective control of annual grasses, broad-leaf weeds and annual sedges (Table 4)

Conclusion

DSR with suitable conservation practices has potential to produce slightly lower or comparable yields as that of TPR and appears to be a viable alternative to overcome the problem of labour and water shortage. Weeds, however, are the major constraints to direct-seeded rice production. To achieve effective, long term and sustainable weed control in direct-seeded system, there is a need to integrate different weed management strategies, such as the use of a stale seeded practice, the rotation of different direct-seeded systems, the use of crop residue as mulches, the use of weed competitive cultivars with high yield potential, appropriate flooding depth and duration, appropriate agronomic practices (row spacing, seeding rates and manual or mechanical weeding), and appropriate herbicide mixtures, timing, and rotation.

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