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Review article

Management of direct seeded rice for enhanced resource - use efficiency

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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. Imminent water crisis, water-demanding nature of traditionally cultivated rice and climbing labour costs ramble the search for alternative management methods to increase water productivity, system sustainability and profitability. Direct seeded rice (DSR) technique is becoming popular nowadays because of its low-input demanding nature. It offers a very exciting opportunity to improve water and environmental sustainability. It involves sowing pre-germinated seeds into a puddled soil surface (wet seeding), standing water (water seeding) or dry seeding into a prepared seedbed (dry seeding). The development of short duration, early-maturing cultivars and efficient nutrient management techniques along with increased adoption of integrated weed management methods have encouraged many farmers to switch from transplanted to DSR culture. This technology is highly mechanized in some developed nations like U.S, Europe and Australia. This shift should substantially reduce crop water requirements and emission of greenhouse gases. The reduced emission of these gases helps in climate change adaptation and mitigation, enhanced nutrient relations, organic matter turnovers, carbon sequestration and also provides the opportunity of crop intensification. However, weed and nematode infestation are major problems, which can cause large yield losses in DSR. Other associated problems with DSR are increased incidences of blast disease crop lodging impaired kernel quality, increased panicle sterility and stagnant yields across the years. Based on the existing evidence, the present paper reviews the integrated package of technologies for DSR, potential advantages and problems associated with DSR, and suggest likely future patterns of changes in rice cultivation.

Keywords: Direct seeded rice, Greenhouse gas emission, Resource conservation, Seed priming, Water saving, Zero tillage, Weeds.
Abbreviations: AWD_alternate wetting and drying; CE_Crop establishment; CEM_Crop establishment methods; CRF_controlled release fertilizers; CT_Conventional tillage; DAS_Days after seeding/sowing; DSR_Direct seeded rice; IGP_Indo-gangetic plains; MG_*Meloidogyne graminicola;*RKN_root-knot nematode; TPR_Transplanted puddled rice; ZT_zero tilled/ tillage.

Introduction

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). But with the elevating shortages of water, the incentive to develop and adopt dry-DSR has increased. Dry-DSR production is negligible in irrigated areas but is practiced traditionally in most of the Asian countries in rainfed upland ecosystems. Water seeding is widely practiced in the United States, primarily to manage weeds such as weedy rice, which are normally difficult to control. Prior to the 1950s, direct seeding was most common, but was gradually replaced by puddled transplanting (Pandey and Velasco 2005; Rao et al., 2007). In Asia, rice is commonly grown by transplanting one month-old seedlings into puddled and continuously flooded soil (land preparation with wet tillage). The advantages of the traditional transplanted puddled rice (TPR) system of crop establishment include increased nutrient availability (e.g. iron, zinc, phosphorus), weed suppression (Surendra et al., 2001), easy seedling establishment, and creating anaerobic conditions to enhance nutrient availability (Sanchez 1973). The transplanted puddled rice (TPR), leads to higher losses of water through puddling, surface evaporation and percolation (Farooq et al., 2011). Repeated puddling adversely affects soil physical properties by dismantling soil aggregates, reducing permeability in subsurface layers, and forming hard-pans at shallow depths (Sharma et al., 2003), all of which can negatively affect the following non-rice upland crop in rotation (Tripathi et al., 2005a). Excessive pumping of water for puddling in peak summers in north west Indo-gangetic plains (IGP) causes problems of declining water table and poor quality water for irrigation on one hand, whereas, in

Table 1. Classification of direct-seeded rice (DSR) system.

System of direct seeding	Seed bed condition and environment	Sowing method practiced	Suitable ecology/environment
Direct seeding in dry bed	Dry seeds are sown in dry and mostly aerobic soil	Broadcasting, Drilling or sowing in rows at depth of 2-3 cm	Mainly in rain fed area, some in irrigated areas with precise water control
Direct seeding in wet bed	Pre germinated seeds sown in puddled soil, may be aerobic or anaerobic	Various	Mostly in favourable rainfed lowlands and irrigated areas with good drainage facility
Direct seeding in Standing Water	Dry or Pre germinated seeds sown mostly in anaerobic condition in standing water	Broadcasting on standing water of 5-10 cm	In areas with red rice or weedy rice problem and in irrigated lowland areas with good land leveling

Table 2. Comparison of grain yield (t ha^{-1}) in direct seeded and transplanted rice under different ecosystems.

Direct seeded rice	Transplanted rice	Rice ecology	Country	Reference
5.50	5.40	Shallow wetland – irrigated	Japan	(Harada et al., 2007)
3.83	3.63	Rainfed lowlands	Thailand and Combodia	(Mitchell et al., 2004)
2.93	3.95	Irrigated	Pakistan	(Farooq et al., 2006a; Farooq et al., 2009c)
5.40	5.30	Favorable irrigated	India and Nepal	(Hobbs et al., 2002)
5.59	5.22	Favorable irrigated	India	(Sharma et al., 2004)
5.38	5.32	Irrigated	S. E. Korea	(Ko and Kang 2000)
3.15	2.99	Unfavourable rainfed lowland	India	(Sarkar et al., 2003)
4.64	4.17	Rainfed lowland-hill	India	(Rath et al., 2000)
6.09	6.35	Rainfed lowland-hill	India	(Tripathi et al., 2005a)
2.56	3.34	Irrigated	Pakistan	(Farooq et al., 2006b; Farooq et al., 2007)
6.6	6.8	Rainfed lowland-hill	India	(Singh et al., 2009a)

eastern IGP, rice transplanting depends mainly on monsoon rains. Furthermore, need of ponded water for customary practice of puddling delays rice transplanting by one to three weeks(Ladha et al., 2009). Huge water inputs, labour costs and labour requirements for TPR have reduced profit margins (Pandey and Velasco, 1999). During the past decade or so, there have been numerous efforts to find alternatives to the conventional practice of conventional till transplanted rice (CT-TPR) (Ladha et al., 2009). Thus, low wages and adequate availability of water favour transplanting, whereas high wages and low water availability favour DSR (Pandey and Velasco 2005). Under present situation of water and labour scarcity, farmers are changing either their rice establishment methods only (from transplanting to direct seeding in puddle soil i.e.Wet-DSR) or both tillage and rice establishment methods (puddle transplanting to dry direct seeding in unpuddled soil i.e. Dry-DSR). DSR is a major opportunity to change production practices to attain optimal plant density and high water productivity in water scarce areas. Adoption of DSR for lowland rice culture would significantly decrease costs of rice production (Flinn and Mandac 1986). In Southeast Asia, DSR is more often adopted in the dry season than in the wet season probably due to better water control; but dry-season rice accounts for less than one-quarter of rice production in this region (Farooq et al., 2011). At present, 23, 26 and 28% of rice is direct-seeded globally, in South Asia and in India, respectively (Rao et al., 2007). In Asia, dry seeding is extensively practiced in rainfed lowlands, uplands, and flood-prone areas, while wet seeding remains a common practice in irrigated areas (Azmi et al., 2005; De Dios et al., 2005). Direct seeding in saturated soil has been widely adopted in southern Brazil, Chile, Venezuela, Cuba, some Caribbean countries, and in certain areas of Colombia (Fischer and Antigua 1996). DSR is being practiced with various modifications of tillage/land preparation and crop establishment (CE) which are used to suit site-specific requirements, but has not gained popularity, even though many research studies suggest its benefits over TPR (Farooq et al., 2008; Singh et al., 2005b). To date, no specific varieties have been developed for this purpose. Existing varieties used for TPR do not appear to be well-adapted for seedling growth in an initially oxygen-depleted micro environment. As a result, farmers often resort to the costly practice of increasing the seeding rate for DSR by 2-3 times. Now, new varieties have been developed for rainfed upland rice ecosystem.It covers about 6.0 million hectares in India, which accounts 13.5% of the total area under rice crop. Rice is direct seeded under dry condition of May-June and remains in the field until harvest in September-early October. Due to shorter monsoon (July to September) period, but moderate annual rainfall of about 850 mm, DSR occupies a major area in eastern zone comprising of Assam, Bihar, Eastern M.P., Orissa, Eastern U.P., West Bengal and North-Eastern Hill region in India. These lands are generally dry, unbunded, and directly seeded. Land utilized in upland rice production can be low lying, drought-prone, rolling, or steep sloping. Because of topography and high porosity, soils do not impound rainwater even for short period of 2-3 days. The varieties suitable for this system of rice cultivation developed by Central Rice Research Institute, Cuttack, India are Sahabhagi Dhan, Bala, Sattari, Kalinga III, Neela, Annada, Heera, Kalyani II, Tara, Vanaprabha, Sneha, Vandana, Dhala Heera, Anjali, Sadabahar, Hazaridhan, Virendra and CR Dhan 40. With respect to yield, both direct seeding (viz. wet, dry or water seeding) and transplanting have similar results (Kukal and Aggarwal 2002). This review sums up an integrated package of technologies for DSR, potential advantages and problems associated with it and likely patterns of changes in DSR.

Direct seeding: present status

In recent years, there has been a shift from TPR to DSR cultivation in several countries of Southeast Asia (Pandey and Velasco 2002). This shift was principally driven by water scarcity issues and expensive labour component for transplanting under acute farm labour shortage (Chan and Nor, 1993). Direct-seeding of rice has the potential to provide several benefits to farmers and the environment over conventional practices of puddling and transplanting. Direct seeding helps reduce water consumption by about 30% (0.9 million liters acre^{-1}) as it eliminates raising of seedlings in a nursery, puddling, transplanting under puddled soil and maintaining 4-5 inches of water at the base of the transplanted seedlings. The farmer saves about Rs 1400 acre^{-1} in cultivation cost. Direct seeding (both wet and dry), on the other hand, avoids nursery raising, seedling uprooting, puddling and transplanting, and thus reduces the labour requirement (Pepsico International, 2011). In addition to labour savings, the demand for labour is spread out over a longer period in DSR than in transplanted rice (Kumar and Ladha, 2011). Conventional tillage (CT-TPR) requires intensive labour in the critical operation of transplanting, which often results in a shortage of labour requirement. Hence, DSR helps in making full use of family labour and having less dependence on hired labour. Due to avoidance of transplant injury, DSR is established earlier than TPR without growth delays and hastens physiological maturity and reduces vulnerability to late-season drought (Tuong 2008).

The yield levels of DSR are comparable to the CT-TPR in many studies. Some reports claim similar or even higher yields of DSR with good management practices (Table2). For instance, substantially higher grain yield was recorded in DSR (3.15 t ha^{-1}) than TPR (2.99 t ha^{-1}), 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; Pandey and Velasco 1999). 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. Yield in DSR is often lower than TPR principally due to poor crop stand, high percentage of panicle sterility, higher weed and root-knot nematode infestation (Singh et al., 2005a). Moreover, cost for weed control is usually higher than TPR. High weed infestation is a major constraint for broader adoption of DSR (Rao et al., 2007). Likewise, micronutrient deficiencies such as Zn and Fe, due to imbalanced N fertilization and high infiltration rates in DSR, are of major concern (Gao et al., 2006). Nonetheless, farmers are inclining to adopt DSR and the area under DSR is increasing as it is more productive and profitable to compensate the production costs.

Comparative emission of greenhouse gases (GHGs) under different crop establishment practices

Flooded rice culture with puddling and transplanting is considered one of the major sources of methane (CH_4) emissions and accounts for 10-20% (50-100 Tg year^{-1}) of total global annual CH_4 emissions (Reiner and Aulakh, 2000). Annually, 4.5 million tonnes of methane is emitted from paddy soils in India (Pepsico International 2011). Due to individual or combined effects of various factors as soil characteristics, climatic conditions, and management such as soil pH, redox potential, soil texture, soil salinity, temperature, rainfall, and water management, amount of CH_4 emission varies between different crop establishment techniques (Aulakh et al., 2001; Harada et al., 2007). Methane emission starts at redox potential of soil below -150 mV and is stimulated at less than -200 mV (Jugsujinda et al., 1996; Masscheleyn et al., 1993). Direct seeding has the potential to decrease CH_4 emissions (Wassmann et al., 2004). Methane emitted from paddy soils can be controlled by various management practices such as reducing the number of irrigations, multiple drainage system during the crop cycle, alternate wetting and drying, *Azolla* application, semi-dry cultivation, arbuscular mycorrhiza and methanotrophs application (Zhao et al., 2006; Tsuruta 2002). Most reports claim lower emission of methane gas under DSR compared to other traditional practices (Table 3). Studies comparing CH_4 emissions from different tillage and crop establishment methods (CEM) under similar water management (continuous flooding/mid-season drainage/intermittent irrigation) in rice revealed that CH_4 emissions were lower in DSR than with CT-TPR (Gupta et al., 2002; Tyagi et al., 2010). In Wet-DSR, the reduction in CH_4emission increased from 16 to 22% under continuous flooding to 82 to 92% under mid-season drainage or intermittent irrigation as compared with CT-TPR under continuous flooding (Corton et al., 2000). 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). In a field experiment in the Philippines, DSR reduced CH_4 emissions by 18% as compared with TPR (Corton et al.,

Table 3. Comparison of Methane gas emission (kg methane ha^{-1}) under direct-seeded and transplanted rice .

S.No	Location/Country	Year/Season	Tillage and Crop establishment method	Water management	Seasonal totalemission (kg CH_4 ha^{-1})	% changes from TPR or puddling	Yield(t ha^{-1})	References
1.	Pantnagar, India	2004	CT-TPR	-	315	0	6.8	(Singh et al., 2009a)
			CT-dry DSR	-	220	-30	6.6	
2.	Modipuram, India	2000-2005	CT-TPR	-	60	0	-	(Pathak et al., 2009)
			CT-dry DSR	-	25	-58	-	
3.	Beijing, China	1991	CT-TPR	Intermittent irrigation	299	0	4.5	(Wang et al., 1999)
			CT-dry DSR	Intermittent irrigation	74	-75	3.6	
4.	South Korea	1998-2000	CT-TPR (30 day old seeding)	Continuous flooding	403	0	5.4	(Ko and Kang 2000)
			CT-TPR (30 day old seeding)	Continuous flooding	424	5	5.4	
			CT-wet seeding	Continuous flooding	371	-8	5.3	
			CT-dry seeding	Continuous flooding	269	-33	-	
5.	Jakenan, Indonesia	1993 WS	CT-TPR	Continuous flooding	229	0	4.7	(Setyanto et al., 2000)
			CT-wet seeding	Continuous flooding	256	12	7.1	
			CT-TPR	Continuous flooding	59	0	4.9	
			CT-dry seeding	Continuous flooding	26	-56	4.4	
6.	Suimon, Japan	1994-1997	CT-TPR	Continuous flooding	271	0	-	(Ishibashi et al., 2007)
			ZT-dry seeding	Continuous flooding	129	-52	-	
7.	Maligaya, Phillipines	1997 WS	CT-TPR	Continuous flooding	89	0	7.9	(Corton et al., 2000)
			CT-wet-DSR	Continuous flooding	75	-16	6.7	
			CT-TPR	Midseason drainage	51	0	7.7	
			CT-wet-DSR	Midseason drainage	48	-6	6.4	

2000). Results of yet another study showed that, just by changing puddling to zero tillage, global warming potential (GWP) declined by 42% in Japan (Harada et al., 2007). Dry-DSR on raised beds or zero tillage (ZT) showed to have potential to reduce CO_2 equivalent per hectare by 40-44% compared with CT-TPR (Pathak et al., 2009). Methane emissions may be suppressed by up to 50% if DSR fields are drained mid-season (Wassmann et al., 2004). Although water-saving technologies including Dry-DSR can reduce CH_4 emissions, relatively more soil aerobic states can also increase N_2O emissions slightly. Nitrous oxide production increases at redox potentials above 250 mV (Hou et al., 2000). Aerobic environment and high moisture content under zero tilled direct seeded rice (ZT-DSR) results in nitrogen losses as N_2O gas and contribute to global warming. In western Japan higher emissions of N_2O under ZT-dry-DSR than in CT-TPR was reported (Ishibashi et al., 2007). These results suggest the need to deploy strategies to reduce N_2O emissions from Dry-DSR for minimizing adverse impacts on the environment. This tradeoff between CH_4 and N_2O emission is a major hurdle in addressing global warming risks and so, strategies must be devised to reduce emissions of both CH_4 and N_2O simultaneously. Developing water management practices in such a way that soil redox potential can be kept at an intermediate range (-100 to +200 mV) to minimize emissions of both CH_4 and N_2O (Hou et al., 2000).

Agro-techniques for enhancing resource- use efficiency in direct seeded rice

The production technology of DSR revolves around weed management, crop establishment and likely shifts in weed flora due to adoption of direct-seeded rice (Ravi Gopal et al., 2010).This technique is being practiced successfully across various countries like U.S.A., Sri Lanka, Malaysia, India, Bangladesh, Combodia, Phillipines, Brazil, China and some Caribbean countries (Kumar and Ladha 2011). In rice producing states of India like Punjab, Haryana, U.P., Bihar, Terai of Uttaranchal, Orissa, Chhattisgarh and West Bengal, a shift towards DSR in suitable eco-systems has been noticed in recent years (Gupta et al., 2006; Ladha et al., 2009). The most important prerequisites for a successful crop of direct seeded rice are (Kumar and Ladha 2011): (1) precise land leveling, (2) good crop establishment , (3) precision water management, (4) weed management and (5) nutrient management

Precise land leveling

The extent of laser leveling in South Asia and China is currently extremely small, compared to that in Australian rice-based systems (50–80% of the rice land) (Lacy and Wilkins 2003). The average field slope in the Indo-gangetic plains (IGP) varies from 1to 3^0 in the northwest (India and Pakistan) and from 3 to 5^0 in the eastern region (eastern India, Nepal, and Bangladesh). Due to a lack of uniform water distribution associated with unevenness of land, the problem of excess or no water causing large yield variability within a field is common and leads to poor establishment of DSR (Kumar and Ladha 2011). In IGP of India on average 8-15 cm deviation in field level in mostly traditionally-leveled fields is observed. This results in poor crop establishment of rice due to unequal distribution of water in soil profile and inundation of newly germinating seedlings at initial stages (Ravi Gopal et al., 2010). Henceforth in 2001, laser assisted precision land leveling was introduced as an entry point for the success of alternative tillage and crop establishment practices (Kamboj et al., 2012). It facilitates uniform and good crop establishment, permits precise and uniform water control and good drainage, reduces the amount of irrigation water needed, increases cultivation area because of fewer bunds, improves input-use efficiency (water, nutrients, and agrochemicals), and hence crop productivity (Jat et al., 2006; Lantican et al., 1999). Laser land leveling results in saving of 20-25 per cent of irrigation water apart from several other benefits (Rickman 2002). DSR yield is correlated with precision of land leveling (Lantican et al., 1999). In Philippines, an estimated average yield loss of 0.9 t ha^{-1}due to deficient land leveling was observed (Lantican et al., 1999). In DSR technique, water productivity was increased by 18.78% under laser leveled fields but the yield under DSR was less (2.96%) compared to TPR. In DSR technique, grain yield and water productivity increased by 2.94 and 14.43% respectively, with laser leveling compared to transplanted rice (Jat et al., 2006).Therefore, laser land-leveling is a precursor technology and rather an entry point for successfulness of DSR through improved water and crop management.

Land preparation for DSR

The method of seedbed preparation depends on tillage method and varies with conventional and conservation tillage systems. Evaluation of raised beds for rice and permanent beds in rice–wheat system commenced more recently (Connor et al., 2002). DSR crop is either sown on flat bed or on raised beds. But, for both, the field (beds) should be free of weeds and precisely leveled at the time of sowing. For conventional till DSR, field should be pulverized to maintain good soil moisture and to maximize soil to seed contact. For zero tilled direct seeded rice (ZT-DSR), existing weeds should be burned down by using herbicides such as paraquat (@ 0.5 kg a.i. ha^{-1} or glyphosate @ 1.0 kg a.i. ha^{-1}) (Gopal et al., 2010; Lantican et al., 1999). Potential agronomic advantages of ZT fields include improved soil structure due to reduced compaction through controlled trafficking, and reduced water logging and timely machinery operations due to better surface drainage. ZT beds also provide the opportunity for mechanical weed control and improved fertilizer placement (Lantican et al., 1999). Establishing crop on raised beds results in savings of about 12 to 60% of irrigation water for direct-seeded and transplanted rice with comparable yields (Balasubramanian et al., 2003; Gupta et al., 2003; Hossain et al., 2003). However, in another study (Beecher et al., 2006) no water saving from the raised bed rice cultivation was observed in comparison to rice grown under conventional flat layout. When grown on raised beds, a variety needs to be able to compensate for the loss in cropped area (caused by the relatively large row spacing between the beds) by producing more productive tillers (Singh et al., 2003).

Seeding time, seed rate and seeding depth

The published literature shows a widespread use of seed rates of up to 200 kg ha^{-1} to grow a DSR crop (Ravi Gopal 2008). High seed rates are used mostly in areas where seed is broadcast with an aim to suppress weeds or when water-seeded (Moody 1977). In the IGP, a seed rate of 20–25 kg ha^{-1} has been found optimum for medium-fine-grain rice cultivars with a spacing of 20 cm between rows and 5 cm within rows (Gopal et al., 2010; Gupta et al., 2006; Sudhir et al., 2007). High seed rates can result in large yield losses due to excessive vegetative growth before anthesis followed by a reduced rate of dry matter production after anthesis (Wells and Faw 1978) and lower foliage N concentration at heading (Dingkuhn et al., 1990). These factors result in higher spikelet sterility and fewer grains per panicle (Kabir et al., 2008). Moreover, dense plant populations at high seed rates can create favourable conditions for diseases, e.g., sheath blight (Guzman and Nieto 1992; Mithrasena and Adikari 1986) and insects (e.g., brown planthoppers) and make plants more prone to lodging (Islam et al., 2008). Lower seed rate can be used for high-tillering varieties and a little higher seed rate for medium-tillering types (Soo et al., 1989). Seeding depth is also critical for all rice varieties but more so for semi-dwarf plant types because of their shorter mesocotyl length compared to conventional tall varieties (Blanche et al., 2009). Placement of seeds too deep or shallow adversely affects the dynamics of seed germination due to weak coleoptiles and rapid drying of the soil surface in peak summers (Ravi Gopal et al., 2010). Therefore, rice should not be drilled deeper than 2.5 cm to maximize uniform crop establishment (Gopal et al., 2010; Kamboj et al., 2012).

Due to non-availability of enough ground water and canal water supplies at the time of nursery raising, excessive preparatory tillage operations and puddling during *kharif* (monsoon) season in India, the planting of DSR crop gets delayed in most rice growing areas. This often leads to terminal water stresses and consequently low productivity of *kharif* rice (Ravi Gopal et al., 2010). Optimum time of planting results in improved rainwater use efficiency by 40-50% and enhances the total productivity of cropping system up to 30% (Kumar and Ladha 2011).In northern western IGP, rice is grown during the monsoon season (*kharif*) when rainfall is high. To optimize the use of monsoon rain, the optimum time for sowing DSR is about 10-15 days prior to onset of monsoon (Gopal et al., 2010;Kamboj et al., 2012; Kumar and Ladha 2011; Ravi Gopal et al., 2010).

Planting machinery

For accurate and precise seeding, rice should be drilled with a multi-crop planter fitted with inclined plate's seed metering systems and inverted T-type tines to sow seeds at a depth of 2.54 – 3.81 cm to have good germination. Normal fluted roller-type seed-cum-fertilizer drills makes it difficult to maintain the seed rate and plant-to-plant spacing as accurate and precise due to continuous seeds fall and breaks them (Gopal et al., 2010; Gupta et al., 2006). With these precise seed-metering planters, better crop establishment with a lower seed rate and more precise plant-to-plant spacing can be done (Gupta et al., 2006). DSR seeded with a planter or a seed cum fertilizer drill have many advantages over conventional puddled transplanting i.e., (i) easier and timely planting, (ii) reduced labour burden at least by 50% (Pandey and Velasco 1998; Singh et al., 1994). Farmers can seed at a lower rate with a normal drill by mixing seed with sand to increase the seed volume and opening of the fluted roller so that breakage of rice can be avoided (Gopal et al., 2010). For ZT-DSR, when only anchored residues are retained, then same multi-crop planter can be used for seeding (Gopal et al., 2010). However, when loose crop residues are present on the soil surface, specialized machines are needed for drilling rice. Recently, different machines have been evaluated and refined for seeding under loose residue, especially after combine harvest in South Asia as turbo happy seeder and rotary disc drill (Singh et al., 2008, Gopal et al., 2010; Kumar and Ladha 2011). Turbo seeder and PCR (row crop precision) planter drilled the seed into a loose residue mulch load of up to 8–10 t ha^{-1}(Gopal et al., 2010). Double disc coulter can drill seeds into a loose residue load of up to 3–4 t ha^{-1}. A limitation with this machine is that, being light weight (0.3 t) it fails to cut through the residues, resulting in some seed and fertilizer being placed on the surface of residues (Gopal et al., 2010. These machineries shred the residues in the narrow strip and places seeds and fertilizer in a single pass and results in higher or comparable yields (Ravi Gopal et al., 2010).

Seed priming

One of the short term and the most pragmatic approaches to overcome the drought stress effects is seed priming (Farooq et al., 2006a). Seed priming tools have the potential to improve emergence and stand establishment under a wide range of field conditions (Phill 1995). These techniques can also enhance rice performance in DSR culture (Farooq et al., 2001). It involves partial hydration to a point where germination-related metabolic processes begin but radical emergence does not occur (Farooq et al., 2006a). Primed seeds usually exhibit increased germination rate, uniform and faster seedlings growth, greater germination uniformity, greater growth, dry matter accumulation, yield, harvest index and sometimes greater total germination percentage (Farooq et al., 2006b; Kaya et al., 2006).This technique allows some metabolic processes to occur without actual germination (Basra et al., 2005). Seed priming techniques, such as hydro-priming (Farooq et al., 2006c); on-farm priming (Harris et al., 1999); osmo-hardening (Farooq et al., 2006d; Farooq et al., 2006b; Farooq et al., 2006a); hardening (Farooq et al., 2004); and priming with growth promoters like growth regulators and vitamins have been successfully employed in DSR (Basra et al., 2005; Farooq et al., 2006b; Farooq et al., 2006a). For primed seed, treatment with fungicide or insecticide should be done post-soaking to control seed borne diseases/insects. Seed can also be soaked in solution having fungicide and antibiotics (Emisan and Streptomycin) for 15-20 hours (Gopal et al., 2010; Gupta et al., 2006; Krausz and Groth 2008). Priming with imidacloprid resulted in increased plant height, root weight, dry matter production, root length, increased yield by 2.1 t ha^{-1} compared to control (non-primed), which was attributed to higher panicle numbers and more filled grains per panicle (Farooq et al., 2011; Mohanasarida and Mathew 2005a; Mohanasarida and Mathew 2005b). *Azospirillum* treatment had the highest shoot:root ratio during early vegetative growth and the maximum tillers (Farooq et al., 2011; Mohanasarida and Mathew 2005a). Seed priming also reduced the need for high seeding rates, but was detrimental for seedling establishment when soil was at or near saturation (Du and Tuong 2002; Farooq et al., 2011). Priming rice seeds for 12 and 24 hours improved crop establishment and subsequent growth (larger leaf area, taller plants, higher root and shoot dry weights measured 4 weeks after sowing) and also had significantly more tillers, panicles and grains per panicle in Ghana (Harris et al., 1999; WARDA 2002). Osmo-hardening with KCl or $CaCl_2$ resulted in faster and uniform seedling emergence from primed seeds, which was attributed to improved alpha amylase activity and increased levels of soluble sugars in these seeds. It also enhanced the starch hydrolysis, making more sugars available for embryo growth, vigorous seedling production and improved growth, kernel yield and quality attributes at maturity (Farooq et al., 2006b; Farooq et al., 2006a).In direct-seeded medium grain rice, osmo-hardening with KCl led to higher kernel yield (3.23 t ha^{-1}), straw yield (9.03 t ha^{-1}) and harvest index (26.34%)as compared to 2.71 and 8.12 t ha^{-1} kernal and straw yield, respectively and 24.02% harvest index under untreated control. This was followed by osmo-hardening with $CaCl_2$, hardening and ascorbic acid priming in order (Farooq et al., 2006a). Likewise, seed priming improved kernel quality in fine grain and medium grain rice under DSR (Farooq et al., 2006b; Farooq et al., 2006a). Moreover, osmo-hardening with $CaCl_2$ improved P, Ca and K uptake, closely followed by osmo-hardening with KCl (Rehman et al., 2010).

Cultivar selection

Currently, no varieties are available that are targeted for alternate tillage and establishment methods, especially in unpuddled or zero-tillage 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., 2006), 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. Varieties suitable for DSR under rainfed uplands are Sahabhagi Dhan, Bala, Sattari, Kalinga III, Neela, Annada, Heera, Kalyani II, Tara, Vanaprabha, Sneha, Vandana, Dhala Heera, Anjali, Sadabahar, Hazaridhan, Virendra and CR Dhan 40, mainly developed by Central Rice Research Institute (CRRI), Cuttack (India). Early planting of photoperiod-insensitive and early heading rice varieties with better drought tolerance are better suited for dry-seeded rice, such as IR36 with 105days duration and good drought tolerance (Gines et al., 1978; Mackill et al., 1996). At IRRI, early heading type of a popular variety IR64 is being developed to provide suitable breeding materials for water saving rice cultivation (Fujita et al., 2007). Ability to germinate under anaerobic conditions and tolerance of early submergence are important for establishing a good DSR crop (Ismail et al., 2009). The modern semi-dwarf cultivars have a short mesocotyl, and this is disadvantageous for good crop establishment, especially when seeds are drilled deeper in the soil (Fukai 2002). It is also reported that semi-dwarf varieties can be as competitive as tall plant-type varieties. Therefore, shorter intermediate height (between tall traditional and modern semi-dwarf) may be more desirable for direct seeding (Fukai 2002). Cultivars having high specific leaf area during vegetative growth and low specific leaf area with high chlorophyll content during the reproductive phase are compatible with high yield and weed competitiveness (Jones et al., 1997b; Jones et al., 1997a). In addition, DSR cultivars must possess enhanced assimilates export ability from the vegetative parts to reproductive parts during the reproductive phase (Dingkuhn et al., 1991a; Dingkuhn et al., 1991b). Lodging resistance is another desirable trait for direct seeding. Intermediate plant height, large stem diameter, thick stem walls, and high lignin content are traits of lodging tolerance (Mackill et al., 1996). In addition, lower positioning of panicles in the plant's canopy is known to be associated with increased tolerance of lodging (Setter et al., 1997). Some varieties and hybrids suitable for DSR are listed in Table 4.

Nutrition and management of micro nutrient deficiency

Land preparation and water management are the principal factors governing the nutrient dynamics in both DSR and TPR systems (Farooq et al., 2011). Since direct seeding follows aerobic cultivation of paddy, it usually results in different nutrient dynamics than the TPR (Farooq et al., 2011). In direct seeding, availability of several nutrients including N, P, S and micronutrients such as Zn and Fe, is likely to be a constraint (Ponnamperuma 1972). In addition, loss of N due to denitrification, volatilization and leaching is likely to be higher in Dry-DSR than in CT-TPR (Davidson 1991; Singh and Singh 1988). Micronutrient deficiencies are of concern in DSR – imbalances of such nutrients (e.g. Zn, Fe, Mn, S and N) result from improper and imbalanced N fertilizer application (Gao et al., 2006). General recommendations for NPK fertilizers are similar to those in puddled transplanted rice, except that a slightly higher dose of N (22.5-30 kg ha^{-1}) is suggested in DSR (Dingkuhn et al., 1991a; Gathala et al., 2011; Kumar and Ladha 2011) to compensate for the higher losses and lower availability of N from soil mineralization at the early stage as well as the longer duration of the crop in the main field in Dry-DSR (Kumar and Ladha 2011). N management of zero till rice during 2008-2009 in Bihar (India) with two distinct cultivars and five nitrogen doses showed that the grain yield was maximum at N dose of 180 kg ha^{-1} for both varieties (Pusa Basmati 1 and Rajendra Mahsuri) in both years compared to lower doses (60 and 120 kg ha^{-1}) as well as of higher doses up to 240 kg ha^{-1} (Ravi Gopal et al., 2010). The general recommendation is to apply a full dose of P and K and one-third N as basal at the time of sowing. Split applications of N are necessary to maximize grain yield and to reduce N losses. The remaining two-third dose of N should be applied in splits and top-dressed in equal parts at active tillering and panicle initiation stages (Kamboj et al., 2012; Ravi Gopal et al., 2010). In addition, N can be managed using a leaf colour chart (LCC) (Alam et al., 2005; Kamboj et al., 2012; Shukla et al., 2004). Two options are recommended for applying fertilizer N using an LCC (IRRI 2010). In the fixed-time option, N is applied at a preset timing of active tillering and panicle initiation and the dose can be adjusted upward or downward based on leaf colour. In the real-time option, farmers monitor the colour of rice leaves at regular intervals of 7–10 days from early tillering (20 DAS) and N is applied whenever the colour is below a critical threshold value (IRRI 2010). For high-yielding inbreds and hybrids, N application should be based on a critical LCC value of 4, whereas, for basmati types, N should be applied at a critical value of 3 (Gopal et al., 2010; Gupta et al., 2006; Shukla et al., 2004).

Slow-release (SRF) or controlled-release N fertilizers (CRFs) offer the advantage of a "one-shot dose" of N and because of their delayed release pattern may better match crop N demand to reduce its losses and labour cost (Shoji et al., 2001). CRF improves N use efficiency (Fashola et al., 2002) and yield compared with untreated urea (Fashola et al., 2002) and due to these benefits CRF with polymer-coated urea is successfully used by Japanese farmers in ZT-dry-DSR (Saigusa 2005). But due to four to eight times higher cost than that of conventional fertilizers, farmers' use of CRF is limited (Shaviv and Mikkelsen 1993). In addition, published results on the performance of SRFs/CRFs compared with conventional fertilizers are not consistent (Kumar and Ladha 2011). Split application of K has also been suggested for direct seeding in medium-textured soil (PhilRice 2002). In these soils, K can be split, with 50% as basal and 50% at early panicle initiation stage (Kumar and Ladha 2011; PhilRice, 2002). Emergence of zinc (Zn) deficiency is now widespread in most of the rice growing soils. Reasons for Zn deficiency in rice fields include low redox potential, high carbonate content and high pH (Mandal et al., 2000). In aerobic soils, Fe oxidation by root-released oxygen reduces

Table 4. Rice varieties (Local, HYV and Hybrids) suitable for direct-seeded rice.

REGIONS	GENOTYPES SUITABLE FOR DSR
Bihar (India)	Satyam, RajendraMahsuri‑I, NDR‑359, Prabhat, Birsa dhan-101, Birsa dhan -104
Eastern Uttar Pradesh (India)	Aditya, NDR‑359, Sarjoo‑52, Mahsoori, Swarna,, Moti, Pusa‑44, KRH-2
Haryana, Punjab, Western U.P. (India)	Pusa‑1121, Pusa Sugandh-5, PRH‑10, Pusa Basmati‑1, Pant Dhan‑12, Sharbati, PHB‑71, Kanchan, Kalinga-3, Heera, Pathra, Sneha, Sahbhagi, Birsa dhan ‑ 101, 104,105, 201 and 202, Saket-4, VLK dhan, Kranti, Satya
Tarai of Uttaranchal(India)	Nidhi, Narendra‑359, Sarvati, PR‑113, Sarjoo‑52
Cambodia	Koshihikari, W42 (Tuong 2008)
Nepal	SonaMasuli, Hardinath, Radha–4, Radha–11, Chaite 2 (Shah and Bhurer 2005)
Thailand	IR57514-PMI-5-B-1-2, IR20 (Naklang et al., 1996)
Japan	RS-15, RS-20 (Tanno et al., 2007)

rhizosphere soil pH and limits release of Zn from highly insoluble fractions for availability to the rice plant (Kim and Bajita 1995). Basal application of zinc to the soil is found to be the best and to avoid its deficiency, application of 25–50 kg ha^{-1} zinc sulphate heptahydrate is recommended. However, if a basal application is missed, the deficiency can be corrected by topdressing up to 45 days. For foliar application, spray of 0.5% zinc sulphate two to three times at intervals of 7-15 days just after the appearance of deficiency symptoms is recommended. A pH below neutral in the rhizosphere increases solubility of P and Zn and hence their availability (Kim and Bajita 1995). The timing and source of Zn application may influence Zn uptake in DSR (Giordano and Mortvedt 1972). Therefore, a shift from TPR to DSR may also affect Zn bioavailability in rice (Gao et al., 2006).

Under aerobic condition, deficiency of iron (Fe) is more pronounced due to oxidation of available ferrous form to unavailable ferric form in soil. For correction of Fe deficiency drilling of 0.5 kg of librel Fe into the soil at sowing time has been found quite promising. Foliar application, however, was observed to be superior to soil application. Foliar-applied Fe is easily translocated acropetally and even retranslocated basipetally. A total of 9 kg Fe ha^{-1} in three splits (40, 60, and 75 DAS) as foliar application (3% of $FeSO_4.7H_2O$ solution) has been found to be effective (Pal et al., 2008). Some experiments revealed that both soil and foliar spray of Fe conjointly results in better yield compared to their sole application. Application of 50 kg ha^{-1} + 2 foliar spray of 2% $FeSO_4.7H_2O$ results in higher grain yield, returns and benefit cost ratio and was comparable to sole soil application of 100 kg $FeSO_4.7H_2O$ ha^{-1} and 3 foliar spray of 2% $FeSO_4.7H_2O$. The crop (Yadav et al., 2011) quickly oxidizes iron sulphate applied under aerobic condition into ferric forms (Fe^{3+}) that is not taken up. After 30 - 35 days of sowing, libmix @ 2 gm per liter of water is sprayed to overcome the deficiencies of Zinc and Iron. To overcome sulphur deficiency, ground application of 2 kg $acre^{-1}$ of librel sulphur needs to be done.

Effective and Efficient Management of Weeds: A major constraint

High weed infestation is the major bottleneck in DSR, especially in dry field conditions (Singh et al., 2009b). Adopting DSR may result in weed flora shifts toward more difficult-to-control and competitive grasses and sedges (Azmi et al., 2005). More than 50 weed species infest direct-seeded rice, causing major losses to rice production worldwide (Caton et al., 2003; Rao et al., 2007). In dry-seeded rice, weeds germinate simultaneously with rice, and there is no water layer to suppress weed growth (Fukai 2002). 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; Singh et al., 2009). In the 1970s, when DSR was introduced into Malaysia and Vietnam, barnyard grass, Asian sprangletop and aromacca grass (*Ischaemum rugosum* L.) were not common in rice fields but dominated rice fields by the 1990’s (Azmi et al., 2005). The DSR fields are more species-rich with greater diversity in weed flora than TPR (Tomita et al., 2003). It favours variable flat sedge (*Cyperus difformis* L.) and water plant (*Sagittaria montevidensis* L.) in Australia and USA, and *Lindernia* spp. in Asia (Gressel 2002). In India, densities of barnyard grass, climbing dayflower (*Commelina diffusa* L.) and purple nut sedge (*Cyperus rotundus* L.) increased in DSR compared with TPR in field experiments from 2000 to 2004 (Singh et al., 2005). It also favours sedges such as *Cyperus difformis, Cyperus iria, Cyperus rotundus,* and *Fimbristylis miliacea* (Gressel 2002; Yaduraju and Mishra 2005). Weed growth reduced grain yield by up to 53 and 74%, respectively (Ramzan 2003), and up to 68–100% for direct seeded *Aus* rice (cropping season in Bangladesh) (Mamun 1990). 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., 2009c). 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 (Maity and Mukherjee 2008), effectiveness of herbicides (Sinha et al., 2005), relative to the dominant weed species and soil conditions at the time of application (Street and Mueller 1993), effect of weather on weeds (Maity and Mukherjee 2008) and effect of combining herbicides and manual weed control (Rao et al., 2007). Adequate integrated weed management (IWM) strategies, including identification of new herbicides that are effective against a wide spectrum of weeds, need to be adopted (FAO 1999). FAO recommends an integrated approach that combines preventive, cultural, and chemical methods that is desirable for effective and sustainable weed control in Dry-DSR (Maity and Mukherjee 2008; Rao et al., 2007; Yaduraju and Mishra 2004). Moreover, weed surveillance may also prove beneficial in selecting suitable herbicides and weed management strategies in a region (Singh et al., 2009). However, cultural methods of weed control are preventive, since they enhance crop growth by precision agronomy, and in doing so maximize crop competition against weeds (Zimdahl 1999). One cultural technique is stale seed bed, which reduces weed emergence as well as the soil weed seedbank (Rao et al., 2007). A 53% lower weed density in Dry-DSR after a stale seedbed was recorded over control (Singh et al., 2009b). 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 greater than 1 cm (Chauhan and Johnson 2010). In large-scale farmer participatory trials in India, combined use of stale seed bedtechnique and a pre-emergence herbicide, pendimethalin, applied within 2 days after seeding (DAS), successfully controlled the weeds in DSR(Singh et al., 2005c). Several pre-emergence herbicides including butachlor, thiobencarb, pendimethalin, oxadiazon, oxyfluorfen and nitrofen, alone or supplemented with hand weeding, resulted in efficient weed control as expressed by reduced weed density and improved crop yields (Moorthy and Manna 1993). Precise land leveling is also effective in reducing the weed population up to 40%, the labour requirement for weeding by 75% and weeding cost by 40% (Rickman 2002). Paired row planting pattern (15-30-15-cm row spacing) in DSR had a great influence on weeds as compared to normal row (23-cm row spacing) planting system (Chauhan and Johnson 2010; Mahajan and Chauhan 2011a). *Sesbania* co-culture technology can reduce the weed population by nearly half without any adverse effect on rice yield (Kamboj et al., 2012). 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 broadleaf weeds than grasses and 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 broadleaf and grass weed density by 76–83% and 20–33%, respectively, and total weed biomass by 37–80% compared with a sole rice crop. Crop residues such as mulch, which may also selectively suppress weeds by covering the soil surface (Mohler 1996; Teosdale et al., 1991) should be part of an integrated weed management program in DSR. A study conducted in India found that wheat residue mulch of 4 t ha^{-1} reduced the emergence of grassy weeds by 44–47% and of broadleaf weeds by 56–72% in dry drill-seeded rice and resulted in 17–22% higher grain yield (Chauhan and Johnson 2010; Singh et al., 2009b; Singh et al., 2007). Allelopathic plant extracts may also be beneficial in the weed management program. Allelopathic crops when exploited in the field by crop rotation (Wu et al., 1999), cover or smother crops, crop residues, mulching (Khanh et al., 2005) and as allelopathic crop water extracts suppress obnoxious weeds (Jabran et al., 2008).A variety of herbicides have been screened and found effective for pre-plant/burn-down, pre-emergence, and post-emergence weed control in direct drill-seeded rice systems. Application of glyphosate (1 kg a.i. ha^{-1}or 0.5-1.0% by volume) and paraquat (0.5 kg a.i. ha^{-1}or 0.5% by volume) are recommended for burn-down application as pre plant herbicides (Gupta et al., 2006). Pendimethalin (1.0 kg a.i. ha^{-1}), oxadiargyl (0.09 kg a.i. ha^{-1}), and pyrazosulfuron (0.02 kg ha^{-1}) have been reported to be effective as pre-emergence herbicides to control weeds in dry direct-seeded rice (Gopal et al., 2010; Gupta et al., 2006; Singh et al., 2009b). Post emergence application (15-25 days after sowing) of bispyribac sodium 25g a.i.ha^{-1}was found very effective on most of grasses like *Echinocloa* spp., but it was weakly effective on perennial sedges, *Digera arensis, Leptocloa, Eragrostis spp etc*. Bispyribac works well in saturated soil conditions (Kamboj et al., 2012; Kumar and Ladha 2011). Weed surveillance may also prove beneficial in selecting suitable herbicides and weed management strategies in a region (Singh et al., 2009). In countries where DSR is widely adopted, herbicide use increased steadily, resulting in the appearance of resistance in weeds against certain herbicides (Farooq et al., 2011; Kumar and Ladha 2011). Incidences of weeds becoming resistant to those herbicides are on the rise (Watanabe et al., 1997); for example, there is evidence that weed species such as dwarf clover (*Marsilea minuta* L.) and globe fringerush (*Fimbristylis miliacea* L.) have developed resistance to phenoxy herbicides (Watanabe et al., 1997). However, no herbicide resistance case has yet been reported in South Asia (Kumar and Ladha 2011).

Precise water management

Substantial water savings are possible from DSR (Dawe 2005). Precise water management, particularly during crop emergence phase (first 7-15 days after sowing), is crucial in direct seeded rice (Balasubramanian and Hill 2002; Kumar et al., 2009). From sowing to emergence, the soil should be kept moist but not saturated to avoid seed rotting. After sowing in dry soil, applying a flush irrigation to wet the soil if it is unlikely to rain followed by saturating the field at the three-leaf stage is essential (Bouman et al., 2007). This practice will not only ensure good rooting and seedling establishment but also enhance the germination of weed seeds (Kamboj et al., 2012). In Northwest India using DSR into non-puddled soils saved 35-57% water (Singh et al., 2002). In these trials, soils were kept near saturation or field capacity unlike the flooded conditions used in puddled-transplanted systems. In small plot DSR trials, the irrigation requirement decreased by 20% (Gupta et al., 2003). Raised bed planting results in better management of available water and reduces the irrigation water demand and water use of crop but at the same time gives slightly lower yield (Balasubramanian and Hill 2002; Gupta et al., 2003; Hossain et al., 2003). DSR on raised beds decreased water use by 12–60%, and increased yield by 10% as compared to TPR, in trials at both experimental stations and on-farm (Gupta et al., 2003). Water productivity in DSR was 0.35 and 0.76 as compared to 0.31 and 0.57 under TPR during 2002 and 2003, respectively, indicating better water-use efficiency (Gill et al., 2006). There are few reports evaluating mulching for rice, apart from those from China, where 20–90% input water savings and weed suppression occurred with plastic and straw mulches in combination with DSR compared with continuously flooded TPR (Lin et al., 2003). Bund management also plays an important role in maintaining uniform water depth and limiting water losses via seepage and leakage (Lantican et al., 1999; Humphreys E et al., 2010). Some researchers (Gupta et al., 2006; Gopal et al., 2010) have recommended avoiding water stress and keeping the soil wet at the following stages: tillering, panicle initiation, and grain filling. Water stress at the time of anthesis results in maximum panicle sterility. In case of DSR, crop established after applying pre-sowing irrigation, first irrigation can be applied 7-10 days after sowing depending on the soil type. When DSR crop is established in dry/ zero tilled (ZT) conditions followed by irrigation, subsequent 1-2 irrigations are required at interval of 3-5 days during crop establishment phase. Subsequent irrigations at interval of 5-7 days need to be applied in DSR crop. During active tillering phase *i.e.* 30-45 days after sowing (DAS) and reproductive phase (Panicle emergence to grain filling stage) optimum moisture (irrigation at 2-3 days interval) is required to be maintained to harvest optimum yields from DSR crop. Irrigation can also be delayed for around 7-15 days depending on soil texture and water table conditions to facilitate deeper rooting and to make seedlings resistant to drought. In a 6-year study conducted in Modipuram, India on sandy-loam soil, it was observed that Dry-DSR can be irrigated safely at the appearance of soil hairline cracks (Gathala et al., 2011). Another study conducted (Sudhir et al., 2007) in Punjab (India) on clay loam soil indicated That -20 Kpa oil tensions at 20 cm depth aresafe for alternate wetting and drying (AWD) irrigation scheduling. This study showed that 33-53% irrigation water can be saved in Dry-DSR with AWD as compared with conventional tilled-transplanted puddled rice (CT-TPR) without compromising grain yield. The development of new cultivars of short to medium duration adapted to water limitations is another approach to reduce irrigation water use (Humphreys et al., 2010). Pressurized irrigation systems (sprinkler, surface, and subsurface drip) have the potential to increase irrigation water use efficiency by providing water to match crop requirements, reducing runoff and deep drainage losses, and generally keeping the soil drier, reducing soil evaporation and increasing the capacity to capture rainfall (Camp 1998). Sprinkler irrigation results in increased grain yield and reduced water application (Kato et al., 2009). In Australia, sprinkler irrigation of rice to replace evaporative loss reduced irrigation water use by 30-70% (Humphreys et al., 1989). Studies in the northwest IGP indicate a little effect in rice when grown on beds on its water productivity (typically around 0.30-0.35 g kg^{-1}) as the decline in water input was accompanied by a similar decline in yield (Sharma et al., 2003; Singh et al., 2003). In spite of several benefits of pressurized irrigation, it has a limitation in rice crop due to closer spacing of crop, drip lines can be a problem until plants are established and it can be resulted in increased cost of production.

Pest and disease management

In general, direct seeded rice is affected by similar pests and diseases as transplanted rice; however, under some conditions there may be greater chance of outbreak of insect-pests and diseases in DSR with high rice plant densities. To enable farmers to reap the full benefits of direct seeding and achieve sustainable crop management, greater efforts are required in developing ecological approaches to pest management and increasing information availability at farm level (Soriano and Reversat 2003). In wet-seeded rice, golden apple snails and rats are also big problems to crop establishment and it is susceptible to various diseases, rice blast being one of the devastating diseases, in both aerobic and direct-seeded cultures (Bonman 1992; Bonman and Leung 2004). In Brazil, blast resistance is the most important target trait for breeding programs in aerobic rice (Breseghelo et al., 2006).

Water deficit and shift from transplanting to direct seeding favours neck blast spread (Kim 1987). Water management directly affects the crop microclimate particularly dew deposition, which affects the life cycle of the pathogens (Sah and Bonman 2008) and indirectly affects crop physiology, thereby influencing host susceptibility (Bonman 1992). Sometimes the attack of arthropod insect pests is reduced in DSR compared with TPR (Oyediran and Heinrichs 2001), but a higher frequency of ragged stunt virus, yellow orange leaf virus, sheath blight and dirty panicle have been observed in DSR (Pongprasert 1995). The increased attack of brown spot disease and plant hoppers in DSR compared with TPR was reported (Savary et al., 2005). The soil borne pathogenic fungus *Gaeumannomyces graminis var. graminis* has been observed in dry-seeded rice without supplemental irrigation in Brazil (Prabhu et al., 2002). The most damaging soil-borne pathogen for aerobic rice is root-knot nematode (RKN) *Meloidogyne graminicola* (MG) (Padgham et al., 2004; Soriano and Reversat 2003). MG is incapable of entering the rice roots under flooded conditions, although it can survive for extended periods under such conditions and attacks rice roots when aerobic conditions come up. In a study in Philippines, RKNs were found to be most damaging pathogen for aerobic rice (Kreye et al., 2009b). Heating soil at 120^0 C for 4 hr is also reported to control soil pathogens (Nie et al., 2007). For poor Asian farmers use of natural plant derived biocides, such as, those from neem (*Azadirachta indica* Juss) as it is cheaper, indigenously available and eco-friendly product. Also pathogens cannot easily develop resistance against neem products because they have more than one molecule responsible for biocidal activity. Neem products have been reported to have fungicidal, insecticidal and nematicidal, and antiviral properties (Prasad 2007). Cultivation of resistant crop varieties and summer ploughing is the pre requisite for efficient management of viral and other diseases/pests. Optimum rate of nitrogenous fertilizers avoid the incidence of brown plant hopper and blast attack. Fumigating the rat burrows with cow dung cake keeping the cow dung balls soaked in kerosene all over the field results in better control of rats and other borrowing animals. Soil application of bio agent as *Trichoderma harzianum* @ 4 g ha^{-1} and *T. virens* @ 8 g ha^{-1} after one week of nematode infestation results in better control and optimum yield of DSR crop (Pankaj et al., 2012). Kreye et al. (2009b) studied the impact of nematicides and biocides on the grain yield of rice. They concluded that the grain yield was maximum and galling of RKN in roots less under DSR crop treated with biocide (nemagel or dazomet @ 50 g a.i. m^{-2}) as compared to transplanted puddled rice.

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. Despite controversies, if properly managed, comparable yield may be obtained from DSR compared with TPR. If not managed efficiently, weeds may cause partial to complete failure of DSR crops. This transition from TPR to DSR also changes the mineral nutrients dynamics of soil, for example, the availability of most micro elements is reduced in DSR. On the research front much needs to be done on the nutrient dynamics in soils under DSR. Also, research is needed on soil ecology in rice soils. Under different rice production zones across the continents need to develop a site-specific package of production technologies for different rice production systems. In DSR culture, water use efficiency (WUE) and productivity may increase if appropriate leveling of lands is done. Early crop vigour, short stature and short duration may also improve WUE. Poor stand establishment is another hindrance in the wide-scale adoption of DSR. Effective seed priming techniques has helped to resolve this issue; but more practical seed priming techniques are yet to be developed. Performance of newly developed rice systems should also be monitored in different ecologies. Varieties capable of synthesizing osmo-protectants and capable of synthesizing stress proteins may be introduced. Although methane emissions aresubstantially reduced in DSR, but, to combat increase in N_2O emission here is need to monitor GHG's emissions and develop strategies to reduce N losses vis-a-vis N_2O emissions under aerobic conditions for safer environment. Effective management strategies, well developed biotechnological and genetic approaches and better understanding of pest and disease dynamics will help to resolve the issues of blast and root knot nematode infestations in DSR. Optimization of crop residue cover needs in systems' perspective. It would be good if the capabilities of farmers to manage natural resources in sustainable manner are enhanced and rice productivity is increased through developing knowledge and technology of direct seeding by way of research and extension activities.

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