CHAPTER SIX

Direct Seeding of Rice: Recent Developments and Future Research Needs

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Contents

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Abstract

Rice (*Oryza sativa* L.), a staple food for more than half of the world population, is commonly grown by transplanting seedlings into puddled soil (wet tillage) in Asia. This production system is labor-, water-, and energy-intensive and is becoming less profitable as these resources are becoming increasingly scarce. It also deteriorates the physical properties of soil, adversely affects the performance of succeeding upland crops, and contributes to methane emissions. These factors demand a major shift from puddled transplanting to direct seeding of rice (DSR) in irrigated rice ecosystems. Direct seeding (especially wet seeding) is widely adopted in some and is spreading to other Asian countries. However, combining dry seeding (Dry-DSR) with zero/reduced tillage (e.g., conservation agriculture (CA)) is gaining momentum as a pathway to address rising water and labor scarcity, and to enhance system sustainability. Published studies show various benefits from direct seeding compared with puddled transplanting, which typically include (1) similar yields; (2) savings in irrigation water, labor, and production costs; (3) higher net economic returns; and (4) a reduction in methane emissions. Despite these benefits, the yields have been variable in some regions, especially with dry seeding combined with reduced/zero tillage due to (1) uneven and poor crop stand, (2) poor weed control, (3) higher spikelet sterility, (4) crop lodging, and (5) poor knowledge of water and nutrient management. In addition, rice varieties currently used for DSR are primarily selected and bred for puddled transplanted rice. Risks associated with a shift from puddled transplanting to DSR include (1) a shift toward hard-to-control weed flora, (2) development of herbicide resistance in weeds, (3) evolution of weedy rice, (4) increases in soil-borne pathogens such as nematodes, (5) higher emissions of nitrous oxide—a potent greenhouse gas , and (6) nutrient disorders, especially N and micronutrients. The objectives of this chapter are to review (1) drivers of the shift from puddled transplanting to DSR; (2) overall crop performance, including resource-use efficiencies of DSR; and (3) lessons from countries where DSR has already been widely adopted. Based on the existing evidence, we present an integrated package of technologies for Dry-DSR, including the identification of rice traits associated with the attainment of optimum grain yield with Dry-DSR.

1. Introduction

Rice is the world's most important crop and is a staple food for more than half of the world's population. Worldwide, rice is grown on 161 million hectares, with an annual production of about 678.7 million tons of paddy (FAO, 2009). About 90% of the world's rice is grown and produced (143 million ha of area with a production of 612 million tons of paddy) in Asia (FAO, 2009). Rice provides 30–75% of the total calories to more than 3 billion Asians (Khush, 2004; von Braun and Bos, 2004). To meet the global rice demand, it is estimated that about 114 million tons of additional milled rice need to be produced by 2035, which is equivalent to an overall increase of 26% in the next 25 years. The possibility of expanding the area under rice in the near future is limited. Therefore, this extra rice production needed has to come from a productivity gain. The major challenge is to achieve this gain with less water, labor, and chemicals, thereby ensuring long-term sustainability.

The Green Revolution technologies (the combination of higher-yielding cultivars, use of agrochemicals, including fertilizer, and irrigation) led to a rapid rise in rice yield, production, and area, which resulted in lower rice

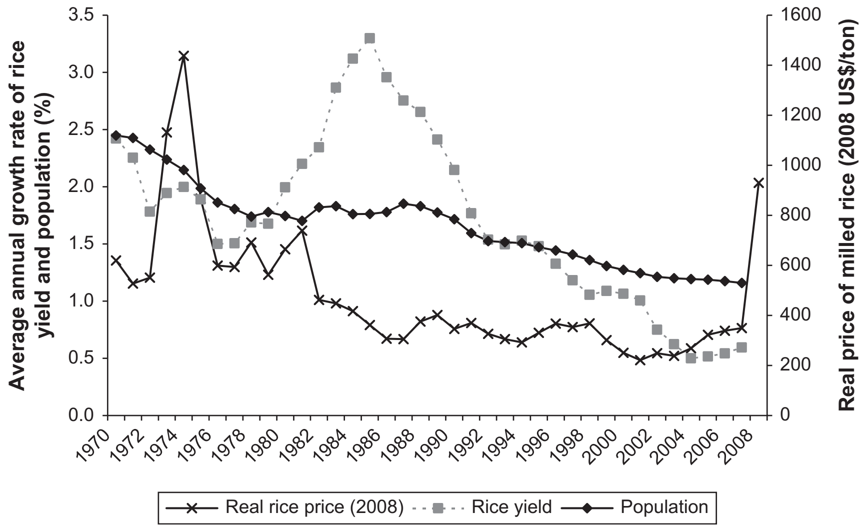

Figure 1 **Trends of average annual growth rate of rice yield and population in Asia and world market rice price (1970–2008). (Rice price: 2008 is as of May 2008 price. Relate to Thai rice 5%-broken deflated by G-5 MUV Index deflator (adjusted based on April 17, 2008, data update). Source: www.worldbank.org.**

prices, thereby benefiting poor consumers in rural and urban areas in Asia (Fig. 1). Although the overall increase in rice production has kept pace with population growth in Asia, growth in rice productivity has been declining since 1985 and, in more recent years, has fallen below the population growth rate (Fig. 1). If continued, this sluggish growth in rice productivity will cause significant imbalances between long-term supply and demand. In recent years, globally, consumption of rice surpassed production, which has led to the depletion of stocks. Current stocks are at their lowest since 1988 (IRRI, 2008). Because of all these factors, the long-term decline in rice price ended in 2001, with a sharp increase in 2008 to a level that had not been seen for decades (IRRI, 2008; Fig. 1).

The productivity and sustainability of rice-based systems are threatened because of (1) the inefficient use of inputs (fertilizer, water, labor); (2) increasing scarcity of resources, especially water and labor; (3) changing climate; (4) the emerging energy crisis and rising fuel prices; (5) the rising cost of cultivation; and (6) emerging socioeconomic changes such as urbanization, migration of labor, preference of nonagricultural work, concerns about farm-related pollution (Ladha *et al.*, 2009). Agronomic management and technological innovations are needed to address these issues in Asia.

In Asia, rice is commonly grown by transplanting seedlings into puddled soil (land preparation with wet tillage). Puddling benefits rice by reducing water percolation losses, controlling weeds, facilitating easy seedling establishment, and creating anaerobic conditions to enhance nutrient availability (Sanchez, 1973). But, repeated puddling adversely affects soil physical properties by destroying soil aggregates, reducing permeability in subsurface layers, and forming hard-pans at shallow depths (Aggarwal *et al.*, 1995; Sharma and De Datta, 1985; Sharma *et al.*, 2003), all of which can negatively effect the following non-rice upland crop in rotation (Hobbs and Gupta, 2000; Tripathi *et al.*, 2005a). Moreover, puddling and transplanting require large amount of water and labor, both of which are becoming increasingly scarce and expensive, making rice production less profitable. Also, the drudgery involved in transplanting—a job largely done by women—is of serious concern. All these factors demand a major shift from puddled-transplanted rice production (CT-TPR) to direct seeding of rice (DSR) in irrigated areas. According to Pandey and Velasco (2005), low wages and adequate availability of water favor transplanting, whereas high wages and low water availability favor DSR. Depending on water and labor scarcity, farmers are changing either their rice establishment methods only (from transplanting to direct seeding in puddled soil [Wet-DSR]) or both tillage and rice establishment methods (puddled transplanting to dry direct seeding in unpuddled soil [Dry-DSR]).

Direct seeding can be categorized as (1) Wet-DSR, in which sprouted rice seeds are broadcast or sown in lines on wet/puddled soil, and (2) Dry-DSR, in which dry rice seeds are drilled or broadcast on unpuddled soil either after dry tillage or zero tillage or on a raised bed. Another category of DSR is water seeding, in which sprouted rice seeds are broadcast in standing water. Wet-DSR is primarily done to manage the labor shortage, and is currently practiced in Malaysia, Thailand, Vietnam, the Philippines, and Sri Lanka (Bhuiyan *et al.*, 1995; Pandey and Velasco, 2002; Weerakoon *et al.*, 2011). But, with the increasing 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 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 (Hill *et al.*, 1991).

Both Dry- and Wet-DSR have the potential to reduce water and labor use compared with CT-TPR. Tabbal *et al.* (2002) in their on-farm studies in the Philippines observed on average 67–104 mm (11–18%) of savings in irrigation water in Wet-DSR compared with CT-TPR when irrigation application criteria was same for both establishment methods. Cabangon *et al.* (2002) in the Muda region of Malaysia found that irrigation water application in Dry-DSR was about 200 mm (40%) less than that in CT-TPR. Similarly, 10–50% savings in water have been claimed with Dry-DSR compared with CT-TPR from India when irrigation application criteria after crop establishment (CE) were either the appearance of hairline cracks or tensiometer-based (−20 kPa at 20-cm depth) (Bhushan *et al.*, 2007; Jat *et al.*, 2009; Sudhir-Yadav *et al.*, 2011a,b). Similar to saving in water, DSR can reduce total labor requirements from 11% to 66% depending on season, location, and type of DSR compared with CT-TPR (Isvilanonda, 2002; Kumar *et al.*, 2009; Rashid *et al.*, 2009; Santhi *et al.*, 1998; Tisch and Paris 1994; Wong and Morooka, 1996). Labor requirements for CE decrease by more than 75% with direct seeding compared with transplanting (Dawe, 2005; Isvilanonda, 2002; Pandey and Velasco, 2002).

The way DSR is currently practiced differs considerably in different countries. Land preparation (tillage), establishment methods, seed rate, water management, weed management, and nutrient management vary from location to location. For example, seeding rates range from 20 to 60 kg ha^{-1} in South Asia to up to 200 kg ha^{-1} in some Southeast Asian countries (de Dios *et al.*, 2005; Gupta *et al.*, 2006; Guyer and Quadranti, 1985). Cleaning and plastering of bunds are an important component of field preparation for both weed and water management in Wet-DSR in Sri Lanka (Weerakoon *et al.*, 2011). A mix of traditional and modern practices based on farmers' long experiences and research innovations are being followed. Although a wealth of available information can lead us to develop DSR technologies that are suitable for wider agroecological conditions, more innovations are needed in the context of emerging challenges that future rice cultivation is likely to face.

During the past decade or so, there have been numerous efforts to find alternatives to the conventional practice of CT-TPR (Ladha *et al.*, 2009). Many of these studies have also considered ways to avoid or minimize extensive land preparation/tillage, which most farmers currently practice. In addition, there is a rich body of literature on case studies of DSR from countries where it is practiced widely. We believe that a systematic inventory and critical review of past and recent work would provide insight to enable us to develop efficient and viable rice production systems needed in the twenty first century. Therefore, the purpose of this review is to take stock of DSR. Specifically, we (1) analyze the reasons for a shift from puddled transplanting to different types of DSR, (2) summarize the current management practices of DSR in different countries, (3) compare the performance of different types of DSR with CT-TPR, (4) summarize the technological package of Dry-DSR including under zero tillage for major rice-based systems in South Asia, and (5) suggest future research needs for making direct-seeding systems more productive and sustainable. We aim to primarily target irrigated or favorable rainfed rice lowlands, which would continue to supply the growing rice demand (presently supplying 75% of world rice from about 50% of total rice area), and where the impact of shifts to DSR in saving of resources (i.e., labor and water) would be the greatest.

Various modifications of tillage/land preparation and CE are used to suit site-specific requirements. For the purpose of simplicity, these modifications are commonly referred to as alternative tillage/CE in this chapter. However, specific modifications are described when necessary.

2. Drivers of the Shift from Puddled Transplanting to Direct Seeding of Rice

2.1. Major drivers

2.1.1. Water scarcity

2.1.1.1. Current rice culture is a major freshwater user and is highly inefficient in its use Rice is a major user of freshwater because of its large area and consumption, which are, two to three times more than other cereals (Barker *et al.*, 1998; Carriger and Vallée, 2007; Tuong *et al.*, 2005). Rice consumes about 50% of total irrigation water used in Asia (Barker *et al.*, 1998) and accounts for about 24–30% of the withdrawal of world total freshwater and 34–43% of the world's irrigation water (Bouman *et al.*, 2007).

Conventional rice production systems (puddled transplanting) require large quantities of water. On average, 2500 l of water are applied, ranging from 800 to more than 5000 l, to produce 1 kg of rough rice (Bouman, 2009). The seasonal water input to rice fields is the combination of water used in land preparation and to compensate for evaporation, transpiration, seepage, and percolation losses during crop growth. Most of the water applied during crop growth is not used directly for transpiration, and is therefore considered lost from fields. Tuong and Bouman (2003) estimated seasonal water input for typical puddled transplanted rice to vary from 660 to 5280 mm depending on growing season, climatic conditions, soil type, and hydrological conditions, with 1000–2000 mm as a typical value in most cases. This consists of (1) 160–1580 mm for land preparation (puddling), with a typical value of 150–250 mm (Tuong, 1999); (2) 400–700 mm for evapotranspiration (ET) (600–700 mm in the dry season and 400–500 mm in the wet season); and (3) 100–3000 mm of unavoidable losses due to percolation and seepage (range of 100–500 mm for heavy clays and 1500–3000 mm for loamy/sandy soils). Tripathi (1990) studied seasonal water input to rice in India, which ranged from 1566 mm in a clay loam soil to 2262 mm in a sandy loam soil, with variations due primarily to deep percolation losses. Gupta *et al.* (2002) estimated water use for rice in the Indo-Gangetic Plains, which varied from 1144 mm in Bihar to 1560 mm in Haryana. In the Philippines, water use has been reported at 1300–1500 mm for the dry season and 1400–1900 mm for the wet season (Bouman *et al.*, 2005).

The water productivity of rice in terms of ET is not different from other C_3 cereals such as wheat (Table 1). The higher water application in rice is mostly due to water requirements for puddling and losses associated with continuous flooding such as seepage and deep percolation losses to groundwater (Hafeez *et al.*, 2007). Seepage and percolation losses vary from 25% to 85% of total water input depending on soil type and water table (25–50% in heavy soils with shallow water tables and 50–85% in coarse-textured soil

Table 1 Amount of water evapotranspired (liters) to produce one kilogram of major cereals

Crop	Photosynthesis type	Minimum	Maximum	Average	Median
			(L)		
Rice	C3	625	1667	917	980
Wheat	C3	588	1667	917	980
Maize	C4	370	909	556	625

Source: Zwart and Bastiaanssen (2004).

with deep water-table depth ≥1.5 m) (Cabangon *et al.*, 2004; Choudhury *et al.*, 2007; Dong *et al.*, 2004; Sharma *et al.*, 2002; Singh *et al.*, 2002a). Although the losses through seepage and percolation are often real for an individual farmer at the field level, they are often not as great at the basin scale since some water is recaptured and used downstream.

2.1.1.2. Water scarcity is increasing and availability of water for agriculture is decreasing Globally, water is becoming an increasingly scarce resource. In the major rice-growing Asian countries, per capita water availability decreased by 34–76% between 1950 and 2005 and is likely to decline by 18–88% by 2050 (Table 2). There are two key types of water scarcity: physical and economic. Physical scarcity occurs when the demand of the population exceeds the available water resources of a region. Economic water scarcity occurs when water is adequate, but is unavailable due to a lack of significant investment in water infrastructure (IWMI, 2000; Rijsberman, 2006).

Irrigated crop production increasingly faces competition for water from the other nonagriculture sectors. At present, irrigated agriculture accounts for 70% and 90% of total freshwater withdrawal globally and in Asia, respectively (Molden *et al.*, 2007; Tabbal *et al.*, 2002). The share of water for agriculture is declining fast, for which the reasons are often location specific, including (1) rising population, (2) falling groundwater table, (3) deteriorating water quality due to chemical pollution, salinization, etc., (4) inefficient irrigation systems, (5) changing food diet, and (6) competition with nonagricultural sectors (domestic, industrial, and environmental).

In Asia, the share of water in agriculture declined from 98% in 1900 to 80% in 2000 and is likely to further decline to 72% by 2020 (Fig. 2). In China, the water share in agriculture dropped from 88% in 1980 to 65% in 2005 and is likely to go down to 50% by 2050 (Fig. 2). Similarly, in other rice-growing Asian countries also, the share of water in agriculture is declining (Fig. 3). These data envisage significant transfers of water from irrigation to other sectors by 2050, thus warranting the development and deployment of highly water use efficient crop production technologies.

Table 2 Per capita water availability in major rice-growing countries of Asia (1950–2050)

Country	1950	1995	2000	2005	2010[a]	2015[a]	2020[a]	2025[a]	2050[a]
					m^3				
Bangladesh	56,411	19,936	16,744	15,393	14,335	13,452	12,703	12,086	10,593
China	5047	2295	2210	2134	2068	2006	1956	1927	1976
India	5831	2244	2000	1844	1717	1611	1525	1457	1292
Indonesia	31,809	12,813	12,325	11,541	10,881	10,361	9952	9609	8781
Japan	6541	4374	4317	4292	4307	4348	4423	4528	5381
Malaysia	74,632	22,642	19,593	17,790	16,336	15,179	14,242	13,503	11,497
Nepal	21,623	7923	6958	6245	5695	5230	4820	4470	3467
Pakistan	11,844	3435	3159	2822	2533	2277	2069	1900	1396
Philippines	15,390	4761	4158	3778	3450	3175	2945	2754	2210
South Korea	3247	1472	1424	1390	1363	1345	1336	1336	1500
Sri Lanka	5626	2410	2302	2212	2117	2041	1990	1961	1990
Thailand	8946	3073	2871	2714	2627	2559	2505	2465	2440
Vietnam	12,553	5095	4780	4472	4223	4015	3836	3684	3367

[a] Projections based on intermediate population growth rate.
Source: Modified from Gardner-Outlaw and Engelman (1997).

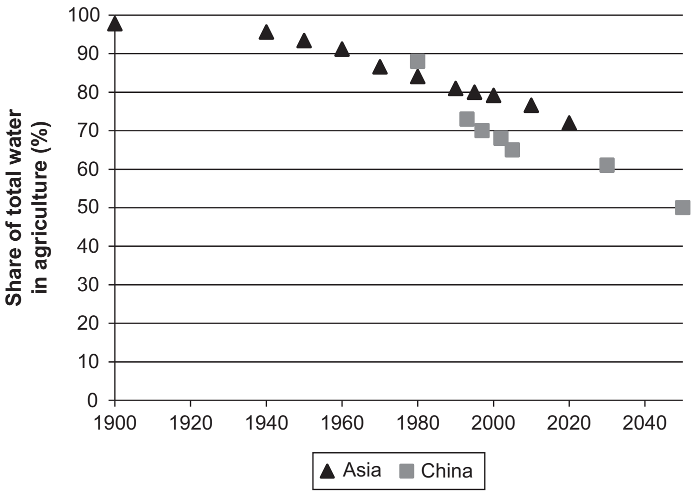

Figure 2 Agriculture's share of water use in Asia and China from 1900 to 2050. Source: State Hydrological Institute (2009) and Jiang (2009).

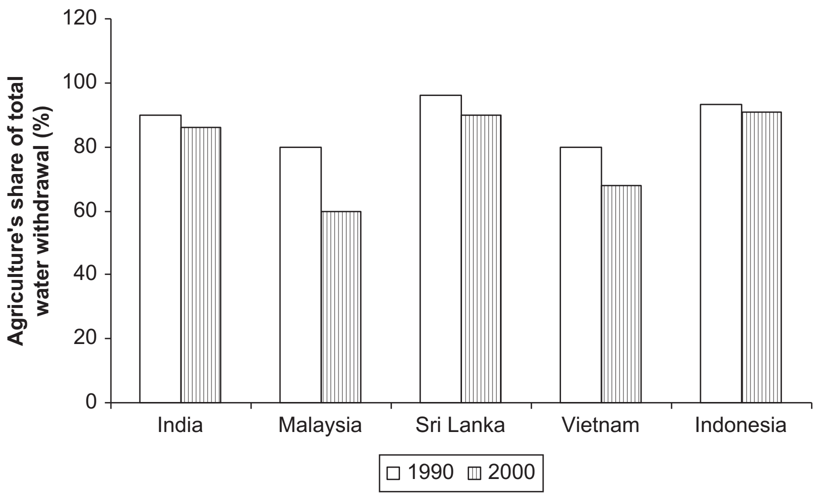

Figure 3 Agriculture's share of total water withdrawal in different rice-growing Asian countries in 1990 and 2000. Source: FAO AQUASTAT (2009).

Another evidence of growing water scarcity is the depleting groundwater resources, especially in South Asia and North China (Postel, 1997; Shah *et al.*, 2007), threatening the most intensive irrigated rice–wheat growing areas. Groundwater tables have fallen in the major rice-growing countries. In the Indian states of Punjab, Haryana, Gujarat, Tamil Nadu, Rajasthan, Maharashtra, and Karnataka, it is falling at 0.5–2 m per year (Singh and Singh, 2002; Tuong and Bouman, 2003). In a recent study, jointly carried out by NASA and the German Aerospace Center (DLR), satellite data showed a groundwater table decline rate of 0.33 m per year in northwestern India (Rodell *et al.*, 2009; UC Irvine, 2009). The study estimated that over a period of 6 years (from August 2002 to October 2008), there was a net loss of 109 km^3 of groundwater in northern India, double the capacity of India's largest surface reservoir (Rodell *et al.*, 2009). In Bangladesh, because of heavy groundwater use, shallow wells are going dry by the end of the dry season (Ahmed *et al.*, 2004).

Similarly, in the North China Plains, many studies have reported increasing groundwater depletion (Bouman *et al.*, 2007; Liu and Yu, 2001; Xia and Chen, 2001). Water tables have dropped on average by 1–3 m per year in the region (Bouman *et al.*, 2007). In the western part of the 3-H basin, the groundwater table dropped from 3–4 m in the 1950s to 20 m in the 1980s and to 30 m in the 1990s (Liu and Xia, 2004). In China, groundwater overexploitation area has increased from 87,000 to 180,000 km^2 since the early 1980s (MWR, 2007).

The decline in the water table is mainly because of the heavy use of groundwater for irrigation as evidenced from intensive groundwater development (tubewells) during the past decades. Groundwater withdrawal structures and groundwater use in South Asian countries and China have increased rapidly (Table 3). For example, in India, the number of groundwater structures (dug wells and tubewells) increased from 3.9 million in 1950–1951 to more than 20 million in 2000 (Fig. 4) and they currently extract 185–210 km^3 $year^{-1}$ of groundwater (Table 3).

Increasing water scarcity has threatened the productivity and sustainability of the irrigated rice system in Asia (Tuong *et al.*, 2004). It is expected that the irrigated rice regions of South and Southeast Asia will experience some degree of water scarcity by 2025. About 13 million ha of Asia's irrigated wet-season rice and 2 million ha of irrigated dry-season rice may

Table 3 Number of groundwater structures (millions) and annual groundwater use (km^3 $year^{-1}$) in South Asian countries and China

Country	Groundwater structures (million)	Groundwater use (km^3 $year^{-1}$)
Bangladesh	0.80	31
China	3.50	75
India	20.00	185–210
Pakistan	0.80	45–55
Nepal Tarai	0.06	<1

Source: Deb Roy and Shah (2002), Shah (2005), and Qureshi *et al.* (2008).

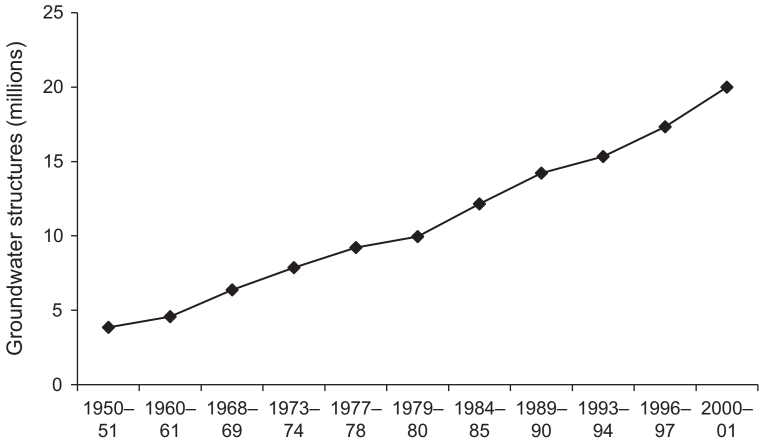

Figure 4 Groundwater withdrawal structures (millions) in India from 1950 to 2001. Sources: Adapted from Singh and Singh (2002) and Shah (2005).

experience physical water scarcity, and about 22 million ha of irrigated dry-season rice may suffer economic water scarcity by 2025 (Tuong and Bouman, 2003).

2.1.1.3. Water scarcity as a driver for direct seeding A grim water scenario in agriculture together with the highly inefficient rice production technologies currently adopted by a majority of farmers globally warrants the exploration of alternative rice production methods, which inherently require less water and are more efficient in water use. DSR provides some opportunities for saving water. Both Dry- and Wet-DSR are more water efficient and have an advantage over CT-TPR (Bhuiyan *et al*., 1995; Dawe, 2005; Humphreys *et al*., 2005; Tabbal *et al*., 2002). However, with increasing shortage of water, Dry-DSR with zero or minimal tillage in which potential savings of both labor and water can be much higher appears to have the greatest potential, especially for irrigated areas of Asia.

2.1.2. The labor shortage and increasing labor wages

CT-TPR is highly labor intensive. Both land preparation (puddling) and CE methods (transplanting) of CT-TPR require a large amount of labor. Rapid economic growth in Asia has increased the demand for labor in nonagricultural sectors, resulting in reduced labor availability for agriculture (Dawe, 2005; Fig. 5). For example, labor forces in agriculture are declining at 0.1–0.4%, with an average of 0.2% per year in Asia. In Bangladesh, Malaysia, and Thailand, the decline rate is much higher (0.25–0.40%), followed by India, the Philippines, and Cambodia (0.18%). In Bangladesh and Malaysia, the proportion of the labor force involved in agriculture dropped from 45% and

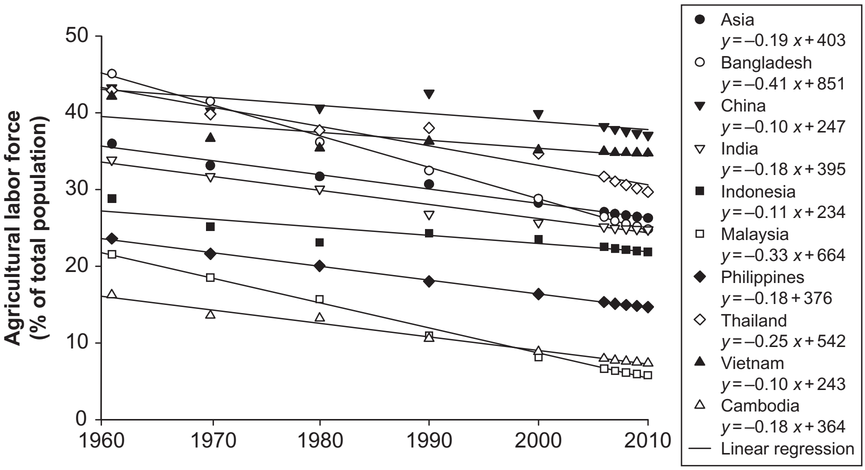

Figure 5 Agricultural labor force (% of total population) in selected Asian countries from 1960 to 2010. Source: IRRI World Rice Statistics database, available online http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250.

22% in 1961 to 25% and 6% in 2008, respectively. Similarly, in Thailand and Vietnam, the agricultural labor force dropped from 40% in the 1960s to 30–35% now. In addition, in the present changing socioeconomic environment in Asia, most people prefer nonagricultural work. Moreover, government policies such as The Mahatma Gandhi National Rural Employment Guarantee Act, introduced by the Indian government in 2005 (GOI, 2011), promising 100 days of paid work in people's home village, is creating a labor scarcity in the cereal bowl of northwest India, which is dependent on millions of migrant laborers from eastern Uttar Pradesh and Bihar for rice transplanting. Because of increasing labor scarcity, labor wages have gone up (e.g., shown in Fig. 6 for four Asian countries), which is making the CT-TPR production system uneconomical in many Asian countries. Because of high labor demand at the time of transplanting, increasing labor scarcity and rising wage rates are forcing farmers to opt for a shift in method of rice establishment from transplanting, which requires 25–50 person-days ha^{-1}, to direct seeding, which in comparison needs about 5 person-days ha^{-1} (Balasubramanian and Hill, 2002; Dawe, 2005).

2.2. Other drivers

2.2.1. Crop intensification and recent developments in DSR production techniques

Although labor and water are the major drivers for the shift from CT-TPR to DSR, economic incentives brought out by DSR through the integration of an additional crop (crop intensification) are another reason for the rapid

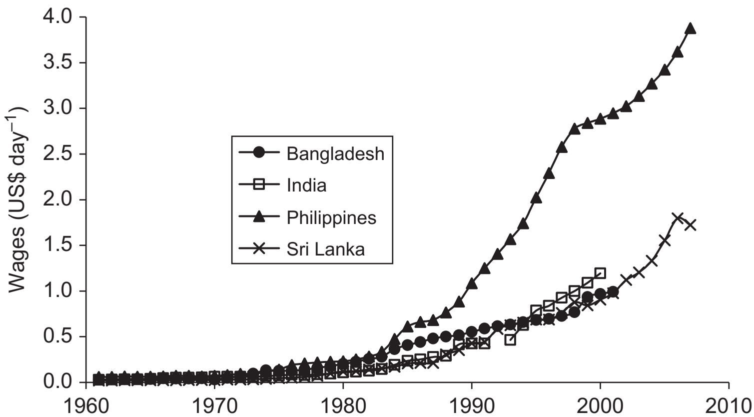

Figure 6 Trend of farm labor wages (US$ day^{-1}) in selected Asian countries from 1960 to 2007. Source: IRRI World Rice Statistics database, available online http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250.

spread/adoption of DSR in some regions. For example, in the Mekong Delta in Vietnam and Iloilo in the Philippines, DSR facilitated double cropping instead of a single crop of transplanted rice (Pandey and Velasco, 2002). Early establishment and short-duration varieties (95–105 days) permitted early harvesting of Dry-DSR in August, therefore, leaving enough time and rainfall to grow another rainfed crop of rice in Long An Province in the Mekong River Delta region of Vietnam. Some farmers can even grow a third crop of rice with supplemental irrigation during December to February (My *et al.*, 1995). DSR has gradually and steadily increased, covering almost 100% of the area, allowing double to triple crops in the region. Notably, the availability of high-yielding short-duration varieties and new herbicides for weed control largely made this shift technically viable (Mortimer *et al.*, 2008; Pandey and Velasco, 2002).

2.2.2. Adverse effects of puddling on soil physical properties and the succeeding non-rice crop

The adverse effects of puddling on soil quality, particularly on soil physical properties and on succeeding non-rice upland crops, are claimed to be other reasons for increased interest in shifting from CT-TPR to Dry-DSR on unpuddled soil or in zero-till conditions where an upland crop is grown after rice (Gopal *et al.*, 2010; Gupta *et al.*, 2006; Ladha *et al.*, 2009). This is especially relevant to the rice–wheat crop rotation, in which land goes through wetting and drying (Ladha *et al.*, 2003). Puddling results in a complete breakdown of soil aggregates, destruction of macropores, and formation of a hard pan at shallow depth. This practice benefits rice in many ways, such as (1) easy weed control, (2) a reduction in deep percolation losses of water and nutrients, (3) ease of transplanting, (4) quick establishment of seedlings, and (5) improved nutrient availability (De Datta, 1981; Sanchez, 1973; Sharma and De Datta, 1985, 1986). Although puddling is known to be beneficial for growing rice, it can adversely affect the growth and yield of subsequent upland crops because of its adverse effects on soil physical properties, which includes poor soil structure, suboptimal permeability in the subsurface layer, and soil compaction (Aggarwal *et al.*, 1995; Gajri *et al.*, 1992, 1999; Gathala *et al.*, 2011; Kirchhof and So, 1996; Kumar *et al.*, 2008a; Meelu *et al.*, 1979). It is therefore important to identify alternatives to puddling (e.g., Dry-DSR), especially in those regions where water is becoming scarce and an upland crop is grown after rice.

The rice–wheat cropping system is practiced on about 18.5 million ha in South Asia and China (Dawe *et al.*, 2004; Ladha *et al.*, 2009), where wheat is grown in the cool and dry weather from November to March/April following rice during the warm and humid/subhumid season from June to October. In this region, many studies have reported on the adverse effect of puddling on the yield of a subsequent wheat crop (Arora *et al.*, 2006; Farooq *et al.*, 2008; Gangwar *et al.*, 2004; Gathala *et al.*, 2011; Hobbs *et al.*, 2002; Jat *et al.*, 2009; Tripathi *et al.*, 2005a,b).

The results of numerous published studies that evaluated the effects of puddling in rice on a subsequent wheat crop have been summarized in Table 4. On average, wheat yields were 9% higher when wheat was grown after Dry-DSR than when grown after CT-TPR. Of 35 studies, in 28 cases, puddling had adverse effects on succeeding wheat productivity (Table 4). Only one study (Singh *et al.*, 2001) reported a positive effect of puddling on the yield of a subsequent wheat crop, and five studies (Hobbs *et al.*, 2002; Malik *et al.*, 2005; McDonald *et al.*, 2006; Sharma *et al.*, 1995, 2005b) mentioned no effect.

Sharma *et al.* (2003) noted that the negative effect of puddling on wheat is more pronounced in medium- to fine-textured soils than in light-textured soils (sandy loam). However, other published results showed no clear relationship with soil type (Table 4). Aggarwal *et al.* (1995) and Kukal and Aggarwal (2003) reported intensity, depth, and duration of puddling as major determinants of effects on soil physical properties. Therefore, it is important to report site history, including the duration of puddling prior to experimentation for an accurate interpretation of the results. Unfortunately, most studies evaluating the effects of puddling on succeeding wheat have not reported site history.

In two medium-term studies conducted at Pantnagar on silty clay loam (5 years) and at Modipuram on sandy loam (7 years), the performance of wheat after either puddled or Dry-DSR was evaluated. The Pantnagar site had 12% higher wheat yield in Dry-DSR plots than in CT-TPR in all 5 years (Singh *et al.*, 2002b). However, at Modipuram, wheat yield was not

Table 4 Effects of tillage and rice establishment methods on grain yield of rice and subsequently grown wheat

S. no.	Location	Soil type	Tillage rice establishment method	Number of crop cycles	Rice yield[a]	Wheat yield[b] (kg ha^{-1})	Change (%) in wheat yield[c]	Reference
1	Pantnagar	Silty clay loam	CT-TPR[d]	2	–	3696 b[e]	0.0	Singh *et al.* (2004)
			Dry-DSR[f]		–	4029 a	9.0	
2	Pantnagar	Silty clay loam	CT-TPR	3	5655 a	3656 b	0.0	Tripathi *et al.* (2005a)
			Dry-DSR		5224 b	3944 a	7.9	
3	Pantnagar	Silty clay loam	CT-TPR	–	5650	4900	0.0	Tripathi (2002)
			Dry-DSR		4970	5500	12.2	
4	Pantnagar	Silty clay loam	CT-TPR	–	–	2890	0.0	Tripathi *et al.* (2005a)
			Dry-DSR		–	3300	14.2	
5	Pantnagar	Silty clay loam	CT-TPR	–	6356	3756	0.0	Tripathi *et al.* (2005a)
			Dry-DSR		6092	4350	15.8	
6	Pantnagar	Silty clay loam	CT-TPR	3	5486 a	3658 b	0.0	Sharma *et al.* (2005a)
			Dry-DSR		5024 b	3923 a	7.2	
7	Pantnagar	Silty clay loam	CT-TPR	2	5895 a	3560 b	0.0	Bajpai and Tripathi (2000)
			Dry-DSR		5380 a	4079 a	14.6	
8	Pantnagar	Silty loam	CT-TPR	3	6100 a	4100 b	0.0	Hobbs *et al.* (2002)
			Dry-DSR		5600 a	4600 a	12.2	
9	Pantnagar	Sandy loam	CT-TPR	6	5600 a	3900 a	0.0	Hobbs *et al.* (2002)
			Dry-DSR		5300 a	4000 a	2.6	
10	Pantnagar	Silty clay loam	CT-TPR	5	–	–	0.0	Singh *et al.* (2002b)
			Dry-DSR		–	–	12.0	
11	Pantnagar	Silty clay loam	CT-TPR	3	5224 a	3677 b	0.0	Sharma *et al.* (2004)
			Dry-DSR		5593 b	4018 a	9.3	

12	Pantnagar	Silty clay loam	CT-TPR	2	–	4170 b	0.0	Rath *et al.* (2000)
			Unpuddled-TPR		-	4640 a	11.3	
13	Pantnagar	Silty clay loam	CT-TPR	2	–	4665 b	0.0	Singh and Singh (2007)
			Dry-DSR		–	5055 a	8.4	
14	Modipuram	Sandy loam	CT-TPR	3	–	4653 b	0.0	Gangwar *et al.* (2004)
			Dry-DSR		–	5287 a	13.6	
15	Modipuram	Sandy loam	CT-TPR	4	7720 b	5000 b	0.0	Gangwar *et al.* (2009)
			Dry-DSR		8300 a	5710 a	14.2	
16	Modipuram	Loam	CT-TPR	2	3720 a	5370 a	0.0	Sharma *et al.* (1995)
			Dry-DSR		3620 a	5380 a	0.2	
17	Modipuram	Sandy loam	CT-TPR		4200 a	3860 b	0.0	Tomar *et al.* (2005)
			Dry-DSR		2310 b	4010 a	3.9	
18	Modipuram	Sandy loam	CT-TPR	2	7500 a	4350 b	0.0	Jat *et al.* (2009)
			Dry-DSR		6400 b	4787 a	10.0	
19	Modipuram	Silty loam	CT-TPR	7	8100 a	4760 b	0.0	Gathala *et al.* (2011)
			Dry-DSR		6820 b	5370 a	12.8	
20	Modipuram	Sandy loam	CT-TPR	2	4930 a	5060 a	0.0	Sharma *et al.* (2005b)
			Unpuddled-TPR		4900 a	5200 a	2.8	
21	Karnal	Clay loam	CT-TPR	2	–	4310 b	0.0	Tripathi *et al.* (2005b)
			Dry-DSR		–	4960 a	15.0	
22	Karnal	Clay loam	CT-TPR	2	–	–	0.0	Tripathi and Chauhan (2001)
			Dry-DSR		–	4500 a	9.0	

(*Continued*)

Table 4 (*Continued*)

S. no.	Location	Soil type	Tillage rice establishment method	Number of crop cycles	Rice yield[a]	Wheat yield[b] (kg ha^{-1})	Change (%) in wheat yield[c]	Reference
23	Karnal	Clay loam	CT-TPR		–	4330	0.0	Tripathi *et al.* (1999)
			Dry-DSR		–	4960	14.5	
24	Kaithal	Clay loam	CT-TPR	2	6530 a	4900 a	0.0	Malik *et al.* (2005)
			Dry-DSR		5430 b	5260 a	7.3	
25	Kaul	Clay loam	CT-TPR	2	7080 a	4630 b	0.0	Ram *et al.* (2006)
			Dry-DSR		4180 b	4900 a	5.8	
26	Kaul	Clay loam	CT-TPR	3	6780 a	4000 b	0.0	Dhiman *et al.* (1998)
			Dry-DSR		5910 b	4340 a	8.5	
27	Bilaspur	Clay loam	CT-TPR	3	5325 a	2980 b	0.0	Parihar (2004)
			Dry-DSR		4764 b	3236 a	8.6	
28	Ghaghraghat, Bahraich, UP	Sandy loam	CT-TPR	3	3333	2780	0.0	Singh *et al.* (2008)
			Dry-DSR		3045	3148	13.2	
29	New Delhi	Sandy clay loam	CT-TPR	3	4467 a	3700 a	0.0	Singh *et al.* (2001)
			Dry-DSR		3033 b	3333 b	−10.0	
30	Bhairahawa, Nepal	Silty clay loam	CT-TPR	2	5300 a	3100 b	0.0	Hobbs *et al.* (2002)
			Dry-DSR		5400 a	3400 a	9.7	
31	Khumaltar, Nepal	Silty loam	CT-TPR	2	6505	3733 a	0.0	McDonald *et al.* (2006)
			Dry-DSR		5710	3683 a	−1.3	

32	Pakistan	Fine silty	CT-TPR	2	4175 a	3910 b	0.0	Farooq *et al.* (2008)
			Dry-DSR		3340 b	4445 a	13.7	
33	Dinajpur, Bangladesh	Sandy loam	CT-TPR	4	3668 a	3768 a	0.0	Meisner *et al.* (2002)
			Dry-DSR		2353 b	3793 a	0.7	
		Average percent increase in yield of wheat grown after Dry-DSR					8.75 ± 0.99	

–, data not available.
[a] Rice yields are the averages of different years or tillage system.
[b] Wheat yields are the averages of different years or tillage system.
[c] Percent change in grain yield of wheat grown after Dry-DSR compared with grown after CT-TPR.
[d] CT-TPR, puddled transplanted rice.
[e] Different letters indicate a significant difference (pair comparison) at $P < 0.05$.
[f] Dry-DSR, dry direct-seeded rice in unpuddled soil.
Source: Modified from Kumar *et al.* (2008a).

different in the first 3 years followed by 0.5–1.0 t ha^{-1} (9–25%) higher yield in Dry-DSR plots in later years (Gathala *et al.*, 2011).

The main reason reported for the lower grain yield of wheat grown after CT-TPR was poor root development in a suboptimal soil physical environment resulting from puddling during the previous rice crop (Aggarwal *et al.*, 1995; Boparai *et al.*, 1992; Chenkual and Acharya, 1990; Ishaq *et al.*, 2001; Oussible *et al.*, 1992). Sadras and Calvino (2001) reported 0.4% lower wheat yield with every centimeter reduction in rooting depth. Ishaq *et al.* (2001) observed that subsoil compaction resulted in a reduction in both water and nutrient use efficiency in wheat by 38% owing to decreased root length. A greater reduction in root growth of wheat was observed in rice-based (e.g., rice–wheat) than in maize-based (e.g., maize–wheat) cropping systems in a sandy loam soil (Sur *et al.*, 1981).

Poor establishment and yields have also been found in other upland crops grown after rice, including soybean in eastern Java (Adisarwanto *et al.*, 1989), chickpea and Indian mustard in India (Gangwar *et al.*, 2008), and mungbean in the Philippines and other Asian countries (IRRI, 1984; Mahata *et al.*, 1990; So and Woodhead, 1987; Varade, 1990; Woodhead, 1990). The physical limitations imposed by puddling were implicated as the major causes of the inferior performance of these upland crops following rice.

However, it is important to note that rice yields in most cases (16 of 24) were higher (8–80%) under CT-TPR than under Dry-DSR. Other studies reported no difference in rice yield between CT-TPR and Dry-DSR (Bajpai and Tripathi, 2000; Hobbs *et al.*, 2002; Sharma *et al.*, 1995, 2005b). This highlights an interesting case of conflict between two crops when grown in rotation with rice. The process of puddling provides many benefits to rice but adversely affects the growth and yield of the subsequent upland crop (i.e., wheat) because of its adverse effects, especially on soil physical properties. This requires an alternative tillage and CE method that provides optimal yield of all the crops in a rotation with maximal efficiency of resource use such as labor and water.

2.2.3. Rising interest in CA

Declining/stagnating crop and factor productivity and a deteriorating resource base in cereal systems such as rice–wheat have led to the promotion of conservation tillage-based agriculture. Conservation tillage involves zero or minimal tillage followed by row seeding using a drill. Conservation tillage, when utilizes crop residue as mulch with improved crop and resource management practices, is termed CA or integrated crop and resource management (ICRM) (Ladha *et al.*, 2009).

Zero tillage, which has been promoted in wheat in the rice–wheat system, is now practiced on about 3 million ha in the Indo-Gangetic Plains of South Asia (Gupta and Seth, 2007; Harrington and Hobbs, 2009). Zero or reduced tillage has had a significant positive impact on wheat productivity, profitability, resource-use efficiency, and farmers' livelihood, especially in those areas where the rice harvest is normally delayed (Erenstein and Laxmi, 2008; Ladha *et al*., 2009). Wider adoption of zero tillage in wheat occurred because of a combination of both increased yields (3–12%, primarily from timely planting) and a reduction in production cost (US$37–92 ha^{-1}, primarily from avoiding tillage) (Erenstein and Laxmi, 2008; Gupta and Seth, 2007; Hobbs and Gupta, 2003). However, unlike wheat, rice continues to be widely grown under conventional intensive tillage (puddling) and CE (transplanting), which is not only resource use inefficient and energy intensive but also delays the planting of wheat. To realize the full benefits of zero tillage, which otherwise are lost by doing puddling in rice, serious efforts are being made to develop zero-tillage rice followed by zero-tillage wheat—commonly referred to as "double zero tillage."

3. Types of Direct-Seeded Rice

Rice can be established by four principal methods: Dry-DSR, Wet-DSR, water seeding, and transplanting. These methods differ from others either in land preparation (tillage) or CE method or in both. Dry-, wet-, and water-seeding, in which seeds are sown directly in the main field instead of transplanting rice seedlings, are commonly referred to as direct seeding. Direct seeding is the oldest method of rice establishment. Prior to the 1950s, direct seeding was most common, but was gradually replaced by puddled transplanting (Grigg, 1974; Pandey and Velasco, 2005; Rao *et al*., 2007).

As it often happens, basic prototype technologies, when introduced to farmers' fields, undergo various modifications to suit local needs and also to optimize the benefits (Ladha *et al*., 2009). There is now a lot of confusion in the terminology used for various versions of direct-seeding practices. Therefore, a standard terminology is essential to communicate better among different groups of stakeholders. Different practices of direct seeding in various ecologies/environments have been classified and compared based on land preparation method, seedbed condition, oxygen level in the vicinity of germinating seed, and methods of sowing (Table 5).

3.1. Dry direct seeding

In Dry-DSR, rice is established using several different methods, including (1) broadcasting of dry seeds on unpuddled soil after either zero tillage (ZT-dry-BCR) or conventional tillage (CT-dry-BCR), (2) dibbled method in a well-prepared field (CT-dry-dibbledR), and (3) drilling of seeds in rows after conventional tillage (CT-dry-DSR), reduced tillage using a power-

Table 5 Major methods of rice direct seeding in various rice ecologies/environments

	Direct-seeding method	Abbreviations	Brief description	Tillage	Seedbed conditions	Seed environment	Depth of seeding	Seeding method/ pattern	Seeding implements	Rice ecology/ environment
A	Dry seeding (Dry-DSR)									
1	Conventionally tilled (dry) broadcast rice	CT-dry-BCR	Land is ploughed, harrowed but not puddled, leveled, and then dry seeds are broadcast manually before the onset of monsoon to use rainfall more effectively. In some cases, seeds are covered with soil by shallow tillage or planking.	Conventional dry tillage	Dry soil (unpuddled)	Aerobic	Surface or 0–3 cm	Broadcasting/ random	Manual	Mostly rainfed upland and flood-prone; some rainfed lowland
2	Conventionally tilled (dry) dibbled rice	CT-dry-dibbledR	Land preparation is same as in CT-dry-BCR but seeds are sown by dibbling methods, placing five to six seeds manually at desired spacing. This is useful in identifying weedy rice	Conventional dry tillage	Dry soil (unpuddled)	Aerobic	1–3 cm	Dibbling/rows	Manual	Mostly rainfed upland and flood-prone; some rainfed lowland
3	Conventionally tilled (dry) drill-seeded rice	CT-dry-DSR	Land preparation is same as in CT-dry-BCR. But, dry seeds are drilled in rows (20-cm apart) in a well-prepared soil (dry or moist) and leveled, followed by one light irrigation	Conventional dry tillage	Dry soil (unpuddled)	Aerobic	2–3 cm	Drilling/rows	Seed-cum-fertilizer drill	Irrigated and favorable rainfed lowland

4	Reduced-tillage (dry) drill-seeded rice with a power-tiller-operated seeder (PTOS)	RT(PTOS)-dry-DSR	In this, PTOS tills the soil at shallow depth (4–5 cm) and drills rice seed at the same time in rows at adjustable distance (20-cm row spacing) in a single operation	Reduced dry tillage (one-pass operation)	Dry soil (unpuddled)	Aerobic	2–3 cm	Drilling/rows	PTOS	Irrigated and favorable rainfed lowland
5	Zero-till dry broadcast rice	ZT-dry-BCR	Fields are flush-irrigated to moisten the soil and allow weeds to germinate. After about 2 weeks, glyphosate/ paraquat is applied to kill weeds. Then, rice seeds (pregerminated) are broadcast in moist soil, followed by a light irrigation, if needed	Zero tillage	Dry soil (unpuddled)	Aerobic	Surface	Broadcasting/ random	Manual	Irrigated and favorable rainfed lowland
6	Zero-till dry drill-seeded rice	ZT-dry-DSR	Fields are flush-irrigated to moisten the soil and allow weeds to germinate. After about 2 weeks, glyphosate/ paraquat is applied to kill weeds. Then, a zero-till drill seeder is used to seed rice in rows (20 cm apart) in moist or dry soil, followed by a light irrigation, if needed.	Zero tillage	Dry soil (unpuddled)	Aerobic	2–3 cm	Drilling/rows	Zero-till-cum-fertilizer drill	Irrigated and favorable rainfed lowland

(*Continued*)

Table 5 (*Continued*)

	Direct-seeding method	Abbreviations	Brief description	Tillage	Seedbed conditions	Seed environment	Depth of seeding	Seeding method/ pattern	Seeding implements	Rice ecology/ environment
7	Raised-bed dry drill-seeded rice	Bed-dry-DSR	A bed former-cum-zero-till drill is used to form 37-cm-wide raised beds and 30-cm-wide furrows in a well-prepared and pulverized soil and rice seeds are sown in rows on both sides of the beds (moist/dry). Frequent light irrigations are applied for quick and uniform germination	Furrow irrigated raised bed	Dry soil (unpuddled)	Aerobic	2–3 cm	Drilling/rows	Bed planter-cum-seed drill	Irrigated and favorable rainfed lowland
B	Wet seeding (Wet-DSR) *Wet seeding on soil surface*									
8	Conventionally tilled (wet) broadcast rice on surface of puddled soil	CT-wet-BCR (surface)	Land is ploughed, puddled, and leveled; pregerminated seeds are sown by broadcasting manually (24-h soaking and 24-h incubation) or by motorized blower (with 24-h soaking and 12-h incubation) 1–2 days after puddling on the surface of puddled (wet) soil after drainage	Both dry and wet tillage (puddling)	Wet soil (puddled)	Mostly aerobic	Surface	Broadcasting/ random	Manual or motorized blower	Irrigated and favorable rainfed lowland

9	Conventionally tilled (wet) drum-sown rice on surface of puddled soil	CT-wet-DrumR (surface)	Land preparation is same as in CT-wet-BCR but pregerminated seeds (with 24-h soaking and 12-h incubation) are sown in rows (18–20 cm apart) on the surface of wet soil by using a drum seeder	Both dry and wet tillage (puddling)	Wet soil (puddled)	Mostly aerobic	Surface	Line sowing	Drum seeder	Irrigated and favorable rainfed lowland
	Wet seeding on subsurface/anaerobic wet seeding									
10	Conventionally tilled (wet) subsurface broadcast rice	CT-wet-BCR (subsurface)	Land is ploughed, puddled, and leveled; pregerminated seeds (with 24-h soaking and 24-h incubation) are sown by broadcasting (manually or by using motorized blower) on wet soil immediately after puddling and suspended mud is allowed to settle down and form a protective cover over the seeds sown	Both dry and wet tillage (puddling)	Wet soil (puddled)	Mostly anaerobic	0.5–1 cm	Broadcasting/ random	Manual or motorized blower	Irrigated and favorable rainfed lowland

(*Continued*)

Table 5 (*Continued*)

	Direct-seeding method	Abbreviations	Brief description	Tillage	Seedbed conditions	Seed environment	Depth of seeding	Seeding method/ pattern	Seeding implements	Rice ecology/ environment
11	Conventionally tilled (wet) drill-seeded rice using anaerobic seeder	CT-wet-DSR (subsurface)	Land is ploughed, puddled, and leveled; pregerminated seeds (with 24-h soaking and 12-h incubation) are drilled in rows 1–2 days after puddling by using an anaerobic seeder fitted with furrow opener and closer	Both dry and wet tillage (puddling)	Wet soil (puddled)	Mostly anaerobic	0.5–1 cm	Drilling/rows	Anaerobic seeder	Irrigated and favorable rainfed lowland
C	Water seeding									
12	Water seeding after dry tillage	Dry-water seeding	Land is dry ploughed, disked, harrowed, leveled but not puddled, and the seedbed is rougher (large clods) than dry seeding. Alternatively, a smooth seedbed is firmed with a grooving implement, which results in a grooved seedbed (2.5-cm depth) on 17.5-25-cm spacing. Pregerminated	Dry tillage	In standing water	Mostly anaerobic	Standing water of 5–10 cm	Broadcasting/ random	Manual or aircraft or motorized blower or tractor-mounted broadcast seeder	Irrigated lowland

			seeds (24-h soaking and 24-h incubation) are then broadcast either manually or using a motorized blower or by a tractor-mounted broadcast seeder with the aircraft in standing water of 10- to 15-cm depth						
13	Water seeding after wet tillage	Wet-water seeding	Land is ploughed, puddled, and leveled as in CT-wet-DSR. Then, pregerminated seeds as explained in dry-water seeding are broadcast in standing water	Dry and wet tillage (puddling)	In standing water	Mostly anaerobic	Standing water of 5–10 cm	Broadcasting/ random	Manual or aircraft or motorized blower or tractor-mounted broadcast seeder	Irrigated lowland

Source: Modified from Ladha *et al.* (2009).

tiller-operated seeder (PTOS) [RT (PTOS)-dry-DSR], zero tillage (ZT-dry-DSR), or raised beds (Bed-dry-DSR) (Table 5). For CT-dry-DSR and ZT-dry-DSR, a seed-cum-fertilizer drill is used, which, after land preparation or in zero-till conditions, places the fertilizer and drills the seeds. The PTOS is a tiller with an attached seeder and a soil-firming roller. It tills the soil at shallow depth (4–5 cm), sows the seeds in rows at adjustable row spacing, and covers them with soil and lightly presses the soil for better seed-to-soil contact, all in a single pass (Khan *et al*., 2009). For Bed-dry-DSR, a bed-planting machine is used, which, after land preparation, forms a bed (37-cm wide raised bed and 30-cm wide furrows), places fertilizer, and drills the seed on both sides of the bed in a single operation (Bhushan *et al*., 2007; Singh *et al*., 2009c). The seedbed condition is dry (unpuddled), and the seed environment is mostly aerobic; thus, this method is known as Dry-DSR. This method is traditionally practiced in rainfed upland, lowland, and flood-prone areas of Asia (Rao *et al*., 2007). However, recently, this method has been gaining importance in irrigated areas where water is becoming scarce. Drill seeding is preferred over broadcasting in irrigated or favorable rainfed areas in both developed and developing countries as it allows line sowing and facilitates weed control between rows, saves seeds and time, and provides better CE. However, in some situations, broadcasting is preferred even in irrigated areas, for example, in Arkansas of the United States, where broadcasting by using an aircraft is common on clay soils or in wet years, when speed of planting is important. In Dry-DSR, land preparation is done before the onset of monsoon, and seeds are sown before the start of the wet season to take advantage of pre-monsoon rainfall for CE and early crop growth.

3.2. Wet direct seeding

In contrast to Dry-DSR, Wet-DSR involves sowing of pregerminated seeds with a radicle varying in size from 1 to 3 mm on or into puddled soil. When pregerminated seeds are sown on the surface of puddled soil, the seed environment is mostly aerobic and this is known as aerobic Wet-DSR. When pregerminated seeds are sown/drilled into puddled soil, the seed environment is mostly anaerobic and this is known as anaerobic Wet-DSR. In both aerobic and anaerobic Wet-DSR, seeds are either broadcast [CT-wet-BCR (surface)] or sown in-line using a drum seeder [CT-wet-DrumR (surface)] (Khan *et al*., 2009; Rashid *et al*., 2009) or an anaerobic seeder [CT-wet-DSR (subsurface)] with a furrow opener and closer (Balasubramanian and Hill, 2002). In CT-wet-DSR (subsurface), seed coating with calcium peroxide to improve oxygenation around germinating seeds can be used. When manual broadcasting is done, seeds are soaked in water for 24 h followed by incubation for 24 h. However, when motorized broadcasting is done, the pregermination period is shortened (24-h soaking and 12-h incubation) to limit root growth for ease of handling (easy flow of sprouted seeds) and to minimize damage, as is the case when a drum seeder is used for row seeding (Balasubramanian and Hill, 2002). A drum seeder is a simple manually operated implement for sowing rice seed on puddled soil. It consists of six drums, each 25 cm long and 55 cm in diameter, connected one after the other on an iron rod having two wheels at the two ends (Khan *et al*., 2009). For the motorized blower, a 3.5-hp mist blower/duster is used, attached with either a 1-m-long blow pipe or a 20- to 30-m-long shower blow pipe (Jaafar *et al*., 1995).

3.3. Water seeding

Water seeding has gained popularity in areas where red rice or weedy rice is becoming a severe problem (Azmi and Johnson, 2009). Aerial water seeding is the most common seeding method used in California (United States), Australia, and European countries to suppress difficult-to-control weeds, including weedy rice. This method is also becoming popular in Malaysia. In this method, pregerminated seeds (24-h soaking and 24-h incubation) are broadcast in standing water on puddled (Wet-water seeding) or unpuddled soil (Dry water seeding). Normally, seeds, because of their relatively heavy weight, sink in standing water, allowing good anchorage. The rice varieties that are used possess good tolerance of a low level of dissolved oxygen, low light, and other stress environments (Balasubramanian and Hill, 2002). In addition to irrigated areas, water seeding is practiced in areas where early flooding occurs and water cannot be drained from the fields.

4. Current Cultivation Practices for Direct-Seeded Rice: Case Studies of the United States, Sri Lanka, and Malaysia

The key cultivation practices of DSR widely used by farmers in the United States, Sri Lanka, and Malaysia are reviewed here with an aim to learn lessons from their experiences. In all three countries, more than 90% of the area is under direct seeding (Table 6). Table 6 provides a comparison of the major characteristics of current practices of DSR followed in the three countries.

4.1. The United States

In the United States, rice is grown in three major areas: (1) the Grand Prairie and Mississippi River delta of Arkansas and Louisiana, (2) the Gulf Coast areas of Louisiana and Texas, and (3) California (Hill *et al*., 1991). The total

Table 6 Comparison of direct-seeding rice production systems in the United States, Sri Lanka, and Malaysia

	United States[a]	Sri Lanka[b]	Malaysia[c]
Area (million ha)[d]	1.20	1.03	0.67
DSR area (%)[e]	100	> 93	> 95
Types of DSR	Dry-DSR 67% and Dry water seeding 33%	Wet- and Dry-DSR. Wet-DSR is dominant. Dry-DSR is only < 5%	Wet- and Dry-DSR. Mostly, it is Wet-DSR. Wet Water seeding is emerging
Average yield (t ha^{-1})[d]	7.7	4.2[f]	3.6
Growing season	March/April to September/October in Arkansas, California, Louisiana, Mississippi, Missouri, and Texas, whereas in Florida, it is grown from mid-February to late October	Maha (main/wet season): Late September to February; Yala (minor/dry season): Early April to early September	Main season (wet season): October to March; off season (dry season): April to September
Mechanization level	High	Less	Moderate
Soil puddling (wet tillage)	Not puddled in both water seeding and Dry-DSR	Puddled in Wet-DSR	Puddled in Wet-DSR and water seeding
Method of land leveling	Laser-aided	Water buffalo or two- or four-wheel tractors using a traditional wooden leveler (wooden plank) or a hand-held leveling board, a wooden blade of about 30″ × 6″ connected to a wooden handle	Motor grader, four-wheel tractor with a rear bucket or bulldozer with or without laser-beam control system
Method of seeding	Drill seeding in Dry-DSR; broadcasting using airplane in water seeding	Broadcasting manually	Broadcasting using knapsack-mounted motorized blower

Seed rate (kg ha^{-1})	70–100 kg ha^{-1} in drill seeding; 100–170 kg ha^{-1} in water seeding	70–220 kg ha^{-1}	120 kg ha^{-1} in Wet-DSR; 150 kg ha^{-1} in water seeding
Method of seed preparation	Dry seeds for drill seeding and sprouted seeds (24- to 36-h soaking and 18- to 24-h incubation) for water seeding	Sprouted seeds (24- to 48-h soaking and 48- to 72-h incubation)	Sprouted seeds (24- to 48-h soaking and 12- to24-h incubation)
Varietal selection and breeding targets	Direct seeding	Direct seeding and transplanting	Direct seeding and transplanting
Irrigation	Fully irrigated	Partially irrigated. Major granary area well irrigated	Partially irrigated
Water management	Dry drill seeding: precise and controlled with the help of precise field leveling and levees (bunds) and good drainage facility. Field is kept moist for optimal crop establishment followed by flooding with 5–10 cm until 2 weeks before harvest. Water seeding: water management ranges from (a) continuous flood, (b) delayed flood in which water is drained for 3–4 weeks after seeding before establishing permanent flood, and (c) pinpoint	Precise and controlled with the help of field leveling and bunds and good drainage system. Puddled water is drained before sowing. During early stage, intermittent irrigation to keep soil moist for optimal and uniform crop stand. About seven DAS, flooding of 1- to 2-cm depth is established to suppress germinating weeds. Water level is then gradually raised with the growth of rice plants	Precise and controlled with the help of proper field leveling, bunds, and drainage system. Puddled water is drained either before sowing or within a day or 2 days after sowing. Water management is similar to that in Sri Lanka

(*Continued*)

Table 6 (*Continued*)

	United States[a]	Sri Lanka[b]	Malaysia[c]
	flood in which water is drained only briefly for 3–5 days after seeding and then similar to continuous flood system		
Fertilizer management	All P, K, Zn, and S applied basal. N is applied either in two (pre-flood and mid-season between panicle initiation and differentiation) or three splits (basal or at seedling, pre-flood, and mid-season). Chlorophyll meter or N analysis of flag leaf is used for mid-season N application	All P is applied as basal. K either basal or in two splits (basal and PI stage). N is applied in three to four splits. After basal, topdressing is based on the status of leaf color	All P, K, and 2/3 N at 15 DAS and remaining N at panicle initiation stage. Chlorophyll meter or LCC is also used for topdressing N application
Major weed control strategies	Integrated weed management with widespread careful use of herbicide and continuous submergence	Integrated weed management with widespread use of herbicides	Integrated weed management with widespread use of herbicides
Herbicide research and development	Highly developed	Moderately developed	Moderately developed
Most common herbicides used	*Preemergence*: Thiobencarb, clomazone, pendimethalin, quinclorac, and molinate	*Preemergence*: Thiobencarb, oxadiazon, butachlor, and molinate	*Preemergence*: Pretilachlor, oxadiazon, molinate, and thiobencarb

	Postemergence: Propanil, bispyribac, penoxsulam, fenoxaprop, cyhalofop, halosulfuron, bensulfuron, carfentrazone, bentazone, triclopyr, acifluorfen, 2,4-D, imazethapyr for Clearfield Rice, and tank mix of propanil with molinate, bensulfuron, halosulfuron, pendimethalin, thiobencarb, triclopyr, bentazone, and bentazone + bensulfuron, etc.	*Postemergence:* Bispyribac, fenoxaprop, sethoxydim, mefenaset, ethoxysulfuron, propanil, MCPA, 2,4-D, oxadiazon + propanil, thiobencarb + propanil, butachlor + propanil, quinclorac + propanil, or propanil + molinate + propanil	*Postemergence*: Bispyribac, fenoxaprop, propanil, pyrazosulfuron, bensulfuron, cinosulfuron, metsulfuron, chlorimuron, 2,4-D, and tank mixture of quinclorac + bensulfuron, molinate + 2,4-D, or bensulfuron, propanil followed by 2,4-D or molinate
Use of herbicide-resistant rice	Imidazoline-resistant rice (IMI-rice) cultivars are widely used	Not used	Locally adapted IMI-rice cultivars MR 220CL1 and MR 220CL2 developed and commercialized in 2010[g]
Emerging issues	(a) Herbicide resistance (b) Shift in weed flora (c) Weedy rice	(a) Shift in weed flora (b) Weedy rice (c) Herbicide resistance	(a) Herbicide resistance (b) Shift in weed flora (c) Weedy rice

[a] Compiled from Hill *et al.* (1997), Slaton (2001), Way and Cockrell (2008), and Saichuk (2009).
[b] Pathinayake *et al.* (1991) and Weerakoon *et al.* (2011).
[c] Hiraoka and Ho (1996), Fuji and Cho (1996), Wah (1998), Karim *et al.* (2004), Azmi and Johnson (2009).
[d] FAO (2010). Data given are of year 2008 for the United States and Malaysia.
[e] Sri Lanka (Weerakoon *et al.*, 2011); Malaysia (Azmi, personal communication), United States (Hill *et al.*, 1991).
[f] Weerakoon *et al.* (2011).
[g] Crop Biotech Update, June 16, 2010 (www.isaaa.org/kc/cropbiotechupdate/article/default.asp?ID=6371).

area is about 1.2 million ha, with an average yield of 7.7 t ha^{-1} (Table 6). All the rice in the United States is direct seeded and can be classified into water seeding (33%) and Dry-DSR (67%), which is mostly drill seeding. In the United States, soil is not puddled like in most tropical countries. Rice production in the United States is highly mechanized, which involves the use of laser technology for precision land leveling, large tractors and heavy-duty implements to prepare seedbeds, aircraft for seeding and pest control, and self-propelled combines with half or full tracks for harvesting in muddy soils. Therefore, unlike Asia, the direct-seeding production system in the United States is the least labor dependent. Accounts of production technologies of dry direct drill seeding and water seeding in the United States summarized below and in Table 6 are adapted from the rice production handbook of California (Hill *et al.*, 1997), Arkansas (Slaton, 2001), Texas (Way and Cockrell, 2008), and Louisiana (Saichuk, 2009).

Fields are precisely leveled using a laser leveler with about 0.2% slope to ensure proper drainage and precise water control for achieving a good crop stand. For dry drill-seeded rice, a weed-free, firm, and well-pulverized seedbed is prepared, which ensures adequate seed-to- soil contact for a uniform crop stand. For the reduced-till system, either a spring or a fall/autumn stale seedbed is practiced in which emerged weeds are killed with nonselective herbicides (paraquat or glyphosate or glufosinate) prior to rice sowing. In zero-till systems, rice is planted directly in the crop residues of the preceding crop, and weeds emerged prior to sowing are killed with nonselective herbicides. For water seeding, a rough and cloddy seedbed is preferred to prevent seeds and seedlings from drifting, and also to facilitate seedling anchorage. In recent years, an implement known as a groover (large "V" roller) is being used to make a corrugated surface for anchoring water-seeded rice.

Seeds at rates varying from 70 to 100 kg ha^{-1} are drilled at a shallow depth (<2.5 cm) to achieve a final plant population of 100–160 plants m^{-2}. A 10% higher seed rate is used in zero-till, and about a 20% higher seed rate is used when seed is broadcast. A much lower seed rate is used for a hybrid variety than for a conventional variety. Although drill seeding is a predominant method in Dry-DSR, broadcasting is preferred on clay soil and in wet years. A higher seed rate (100–170 kg ha^{-1}) is used in water seeding to compensate for greater seed loss due to standing water. In this method, pregerminated seeds are used, in which seeds are soaked in water for 24–36 h and then drained for 18–24 h for sprouting. Soaking helps increase seed weight by 25%, which in turn facilitates sinking to the soil surface and reduces seed floating on the soil surface. Sprouting also speeds up the rate of emergence.

High-yielding varieties have been developed through breeding specifically targeted for direct seeding, including zero-till. Almost all farmers use certified seeds, which ensure seed purity and high germination, and they are free from weed seeds, including red rice. Because of the use of certified seeds coupled with the practice of water seeding, the problem of red rice is kept under control in California. Herbicide-resistant varieties (Clearfield Rice) are preferred by farmers in areas infested with red/weedy rice.

All rice is fully irrigated with precise and controlled water management. Levees (bunds) are formed at every 5–8-cm drop in elevation for good water control. Land leveling plays a major role in precise water management. In dry seeding, the field is kept moist in the early season to ensure optimal CE, followed by a permanent flood of 5–10 cm throughout the growing season. At panicle development, it is critical to maintain flood to avoid a yield penalty. In water-seeded rice, water management is categorized as (a) a continuous flood system, (b) delayed flood system, and (c) pinpoint flood system (Table 6). Pinpoint water management is the most common one.

In the dry drill-seeded system, all P, K, Zn, and S are applied as basal. Prior to 1995, a three-way split application of N was common (basal at seeding or seedling stage, at pre-flood, and at reproductive stage between panicle initiation and differentiation). However, recently, two splits instead of three are preferred (pre-flood and mid-season) because of more precise water management and planting of short-duration cultivars (Snyder and Slaton, 2001). A chlorophyll meter or N analysis of the flag leaf is also used to determine the need of mid-season N application (Snyder and Slaton, 2001).

Weeds are controlled in an integrated manner by employing mechanical, cultural (certified seeds, crop rotation, good seedbed, land leveling, and precise water management), and chemical practices. However, the availability of a range of pre-, delayed pre-, and postemergence herbicides has played a major role in keeping weeds under control in direct seeding. Early seasonal weed control is critical for DSR success; therefore, preemergence herbicides with residual effects are used for achieving initial good control. Evolution of resistance in weeds against the most commonly used herbicides for their control and red rice infestation are the major issues in Dry-DSR in the United States. In recent years, more and more Clearfield Rice technology (rice resistant to imazethapyr, a broad-spectrum herbicide) is practiced on a large area to overcome the constraints imposed by red rice and other weeds that have developed resistance to commonly used herbicides.

4.2. Sri Lanka

Based on the total annual rainfall, Sri Lanka is broadly divided into three climatic zones: dry zone (DZ), intermediate zone (IZ), and wet zone (WZ) with annual rainfall <1500, 1500–2500, and >2500, respectively. There are two rice-growing seasons: (a) *Maha* (main season) from late September to February, during which inter-monsoon and northeast monsoon rains are well distributed all over the island, and (b) *Yala* (minor-season) from early April to early September, during which rain is mostly restricted to the southwest region. The area under rice cultivation is 0.7 million ha of which 0.6 and 0.4 million ha are being cultivated during the major and minor seasons, respectively, with an average yield of 4.2 t/ha (Table 6). Direct seeding is the predominant method (93%), with the majority under wet seeding, in which sprouted seeds are broadcast on puddled soil (CT-wet-BCR). The area under Dry-DSR is less than 5%, in which dry seeds are broadcast on dry unpuddled soil (CT-dry-BCR) (Table 6). The key production technologies of Wet-DSR in Sri Lanka are summarized in Table 6, which has largely been adapted from Pathinayake *et al*. (1991) and Weerakoon *et al*. (2011).

Cleaning and plastering of bunds followed by two ploughings and land leveling are the key land preparation and water management practices in Sri Lanka. These practices are traditionally developed and perfected by the farmers, and continue to be widely practiced. The cleaning and plastering of bunds help in (1) reducing weed incidence on bunds and their spread to the main field, (2) minimizing seepage of water and nutrients, and (3) ensuring good water management. With the onset of monsoon, fields are ploughed and puddled using either a two- or a four-wheel tractor, with buffaloes or manual land preparation in low-country WZs where fields are boggy or too wet, and the soil is too sticky. Fields are then leveled using either a water buffalo or a two- or four-wheel tractor in such a way that there is a small gradient toward the drainage outlet of the field. Leveling ensures good water control, including drainage, critical at the early stage for good and uniform CE. Tractor-mounted precision levelers are not used in Sri Lanka (Table 6). Excess standing water is drained, and seeds are broadcast manually on the same day of leveling if the soil is not very loose. Otherwise, sowing is delayed until the soil surface becomes a little harder.

Drainage is crucial for growing a successful Wet-DSR crop. This is achieved by preparing a network of primary, secondary, and tertiary drainage canals in the fields. After construction of the main (primary) drain, shallow and lateral (secondary and tertiary) drains are connected to the outlets to drain out the remaining water from the field. In addition, to ensure a good crop stand, seeds are processed to maximize germination and minimize weed seed contamination. For this, seeds of desired cultivars are cleaned to remove empty grains and chaff, followed by soaking in water to remove half-filled grains and for sprouting. Seed depth (1–2 cm) is also critical for good CE. The puddled soil is kept firm enough to keep broadcast seed partially buried in the soil. Farmers believe that, if the mud is too soft or dry, germination is adversely affected. A seed rate of 100 kg ha^{-1} is recommended but seed used by farmers varies from 70 to 220 kg ha^{-1}. Farmers using a high seed rate believe that this helps in suppressing weeds.

High-yielding medium-duration (105 days) varieties suitable for Wet-DSR are most commonly used by farmers except in the minor irrigation scheme and in the WZ where water is not a constraint and relatively longer duration cultivars of over 105 days are preferred. Another reason for using long-duration varieties in the WZ and in some areas of the IZ is to avoid heavy mid-season rain coinciding with flowering. Like in the United States, the breeding program targets direct seeding. All new rice lines are field-tested under a direct-seeded environment in different agroecological zones before recommending them to farmers. All the released varieties in Sri Lanka have adequate mechanisms of resistance against major diseases and insect pests, and lodging.

Water is precisely managed. During the early stage (after rice seed germination), fields are irrigated intermittently to avoid desiccation of rice seedlings and to ensure a uniform crop stand. Later, 7 days after sowing, fields are flooded to a depth of 1–2 cm to suppress germinating weeds. Water depth is gradually increased with the growth of rice plants.

All P is applied basal and K in two splits (basal and at panicle initiation). Nitrogen is applied in three or four splits. After basal application, topdressing is done based on the status of leaf color. But the quantity of N applied varies with the experience of rice farming and financial status of farmers.

Weeds are controlled by the integration of cultural and chemical methods. Weed pressure is minimized initially by land preparation and water management (shallow flooding of fields with water at seven DAS to suppress weed germination). Almost all the farmers depend on herbicides for weed control. The availability of effective and selective herbicides suitable for direct-seeding conditions in the country has played an important role in achieving good weed control. Two major issues that have emerged with the continuous use of Wet-DSR are (1) the evolution of herbicide resistance in weeds and (2) infestation of rice with weedy rice.

4.3. Malaysia

In Malaysia, rice is grown mainly in two seasons in a year: (i) the main/wet season from October to March and (ii) the off season from April to September (Table 6). The total cultivated area is 0.67 million ha, of which >95% is Wet-DSR. During the main season, rainfall is usually sufficient to meet the water requirement. But, in the off-season, the crop is irrigated from a nearby canal. Unlike Sri Lanka and somewhat similar to the United States, direct seeding is mechanized in Malaysia. Puddling, which was done earlier with draft animals, is replaced with pedestrian power tillers and four-wheel-drive tractors. Similarly, manual harvesting was common in the past but is now done by combines. The key production technologies of Malaysian Wet-DSR described here and presented in

Table 6 are adapted from Hiraoka and Ho (1996), Fuji and Cho (1996), Wah (1998), Karim *et al.* (2004), and Azmi and Johnson (2009).

Seeding is done on drained or shallow flooded puddled and precisely leveled fields by broadcasting pregerminated seeds using a knapsack-mounted motorized blower. When sowing is done in shallow standing water, the field is drained within a day or two to ensure a good crop stand as young plants can tolerate continuous flooding only up to a maximum of 2 or 3 days. Therefore, the provision to drain excess water is important in Wet-DSR to ensure a uniform and good establishment. Traditionally, drainage is achieved by making temporary or semi-permanent ditches of various sizes. Land leveling, considered a prerequisite, is carried out by using a tractor with a rear bucket or a motor grader with a laser control system. Water and fertilizer management are similar to those practiced in Sri Lanka.

In the beginning, when Wet-DSR had just started in Malaysia, yields used to be inconsistent and fluctuated. This was because of inadequate knowledge of land, crop, and water management, and the unavailability of suitable cultivars for DSR conditions. Subsequently, research and infrastructure improvement, especially of irrigation and cultural management, have led to higher yields. Besides, priority was given to developing cultivars specifically bred for direct-seeding conditions, which resulted in additional yield gains. Direct seeding, after its introduction in the late 1970s, has now emerged as a viable alternative to transplanting and has sustained rice production in the country. Crop lodging is still a problem in Wet-DSR, for which cultivar selection has been advocated. Like in Sri Lanka and the United States, in Malaysia too, there are reports of a shift in weed flora, the appearance of weedy rice, and resistance in weeds against herbicides.

5. The Performance of Direct-Seeded Rice Compared with Transplanted Rice

In this section, the performance of different types of DSR methods varying in tillage and method of establishment is compared with that of conventional puddled transplanted rice (CT-TPR). The performance criteria used included grain yield, irrigation water use, labor use, economics, and greenhouse gas (GHG) emissions. The data used for this analysis largely came from 215 studies (165 researcher-managed and 50 farmer-managed), from six major rice-growing Asian countries (India, Nepal, Pakistan, Bangladesh, the Philippines, and Thailand). Only those studies were considered in which a control (puddling followed by rice transplanting) was included for comparison. In studies in which other factors (e.g., planting dates, fertilizer level, weed control, water management, and genotypes) were evaluated, averages across all factors were considered. Likewise, if the studies were conducted over several years, averages of all the years were used. As discussed earlier, farmers often modify technologies to suit their needs, and several variants of DSR practices were found in the literature. We grouped those in which minor modifications were made. Studies that did not provide a clear description of establishment methods (e.g., broadcast or drill seeding) were grouped into direct seeding. To compare performance, changes and percent change in various parameters were estimated for each study compared with CT-TPR.

Because of the unbalanced nature of the data, the analysis was performed using a mixed model procedure (SAS, 2001) with studies as replicates and a varying number of treatments in each replicate. Treatment effects were always considered as a fixed effect. For country-wise analysis, a study/replication was considered as a random effect, whereas, for combined analysis, country, replication/study nested within a country [replication (country)], and treatment × country were taken as random effects. For yield, treatment × country interaction was significant but, for cost and net income, the interaction was nonsignificant; therefore, only treatment (fixed effect) and replication (random effect) were included in the model statement for cost and net income analysis. The analysis estimated an adjusted mean of the original, change, and percent change data for each treatment. However, all interpretations were made on an adjusted mean of change data only and treatment means were compared against the control (puddled transplanted rice) at the 5% level of significance. A negative change indicated a lower value in DSR treatment than in CT-TPR, and the reverse was true when there was a positive change.

5.1. Rice grain yield

Our analysis showed that the performance of different types of DSR methods varied with countries as suggested by significant country × treatment (tillage/CE) interaction ($P = 0.023$). In India, yields were significantly lower (9.2–28.5%) in Dry-DSR than in CT-TPR (Table 7 and Fig. 7). Yields of Bed-dry-DSR were lower by 29%, whereas those of CT-dry-DSR and ZT-dry-DSR were lower by 9.2–10.3%. In Pakistan, yields of both Wet- and Dry-DSR were 12.7–21.0% lower than CT-TPR. In Bangladesh and the Philippines, yields of CT-wet-DSR were higher (8.6–18.5%) than those of CT-TPR, whereas in all other countries, yields were similar to those of CT-TPR. In general, line/drill seeding (compared with broadcasting) and Wet-DSR (compared with Dry-DSR) yielded more.

Apart from the six countries we analyzed, Wet-DSR performed similar to CT-TPR in Cambodia (Rickman *et al.*, 2001). Similarly, Mitchell *et al.* (2004) reported that DSR performed similar to CT-TPR also in Laos, Thailand, and Cambodia.

Table 7 Analysis of rice grain yield comparisons between conventional puddled transplanting and various alternative tillage and crop establishment methods in Asia

Country	Tillage and CE methods[a]	N[b]	Adjusted mean yield (t ha^{-1})[c]	Δ Yield (t ha^{-1})[d]	P value[e]	% Change
India	CT-TPR	98	5.48	–	–	–
	CT-wet-BCR	26	5.12	−0.39	0.0056	−7.5
	CT-wet-DSR	35	5.34	−0.10	NS	−1.9
	CT-dry-BCR	3	4.18	−1.20	0.0005	−26.5
	CT-dry-DSR	66	4.95	−0.53	<0.0001	−9.2
	Bed-dry-DSR	22	3.65	−1.75	<0.0001	−28.5
	ZT-dry-DSR	19	4.86	−0.65	<0.0001	−10.3
Bangladesh	CT-TPR	30	5.30	–	–	–
	CT-wet-BCR	16	5.45	0.12	NS	2.9
	CT-wet-DSR	12	5.66	0.46	0.0010	8.6
	ZT-dry-BCR	4	5.24	−0.24	NS	−2.0
	ZT-dry-DSR	6	5.50	0.08	NS	2.3
Pakistan	CT-TPR	12	3.95	–	–	–
	CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	3	3.06	−0.86	0.0016	−19.8
	CT-dry-DSR	10	3.40	−0.55	0.0045	−12.7
	Bed-dry-DSR	5	3.42	−0.53	0.0156	−12.7
	ZT-dry-DSR	3	3.12	−0.90	0.0011	−21.0
Nepal	CT-TPR	14	4.80	–	–	–
	CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	6	5.00	0.24	NS	5.5
	CT/RT-dry-DSR	15	4.80	0.00	NS	0
	Bed-dry-DSR	3	4.55	−0.29	NS	−4.6
Philippines	CT-TPR	33	5.94	–	–	–
	CT-wet-BCR	25	6.02	0.08	NS	0.6
	CT-wet-DSR	7	6.84	0.90	0.0005	18.5
	CT-dry-BCR	4	6.04	0.17	NS	0.8
	CT-dry-DSR	6	6.07	0.23	NS	4.4
Thailand	CT-TPR	24	3.63	–	–	–
	CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	16	3.73	0.24	NS	9
	CT-dry-seeding (CT-dry-BCR, CT-dry-DSR)	9	3.83	−0.07	NS	2.5

Table 7 (*Continued*)

Country	Tillage and CE methods[a]	N^b	Adjusted mean yield (t ha^{-1})[c]	Δ Yield (t ha^{-1})[d]	*P* value[e]	% Change
	ZT-dry-seeding (ZT-dry-BCR, ZT-dry-DSW)	4	3.61	−0.20	NS	−3.4

NS, nonsignificant.
[a] Refer to Table 5 for a description of tillage and CE methods.
[b] Number of studies.
[c] Adjusted mean yield calculated using SAS mixed model analysis.
[d] Adjusted mean of change in yield over CT-TPR calculated using SAS mixed model analysis.
[e] Based on analysis of change (Δ yield) data (pair comparison with CT-TPR).

It is also important to note that the performance of DSR can also vary from location to location within a country. For example, in the northwestern IGP, there is a tendency of a yield penalty with Dry-DSR (Gathala *et al.*, 2011; Jat *et al.*, 2009; Saharawat *et al.*, 2009) but not in the eastern IGP (Singh *et al.*, 2009c). A possible reason for this differential performance in northwestern versus eastern IGP is lower rainfall in the former (400–750 mm $year^{-1}$) than in the latter (1000–1500 mm $year^{-1}$) (Gupta and Seth 2007). Flooding of rice after successful establishment can alleviate nutrient deficiencies (i.e., Fe and Zn) and soil-borne diseases (i.e., nematodes). Also in the eastern IGP, current yields of CT-TPR are much lower than that in the northwestern IGP; therefore, it is easier to achieve equivalent yield with DSR.

The causes of lower yield in Wet- and Dry-DSR reported by researchers in different production zones may include (1) uneven or poor CE (Rickman *et al.*, 2001), (2) inadequate weed control (Johnson and Mortimer, 2005; Kumar *et al.*, 2008a; Rao *et al.*, 2007; Singh *et al.*, 2005), (3) higher spikelet sterility than in puddled transplanting (Bhushan *et al.*, 2007; Choudhury *et al.*, 2007), (4) higher crop lodging, especially in wet seeding and broadcasting (Fukai, 2002; Ho and Romli, 2002; Rickman *et al.*, 2001; Yoshinaga, 2005), and (5) insufficient knowledge of water and nutrient management (micronutrient deficiencies) (Choudhury *et al.*, 2007; Humphreys *et al.*, 2010; Sharma *et al.*, 2002; Singh *et al.*, 2002a; Yadvinder-Singh *et al.*, 2008; Sudhir-Yadav *et al.*, 2011a,b).

In studies in which these constraints have been addressed, equivalent or higher yields are often reported under DSR than in CT-TPR (Bhushan *et al.*, 2007; San-oh *et al.*, 2004; Tabbal *et al.*, 2002; Yoshinaga *et al.*, 2001). Technologies have been developed or progress has been made to overcome some of the constraints in DSR. For example, (1) coating of pregerminated seeds with calcium peroxide to facilitate seedling establishment in anaerobic conditions in wet seeding or water seeding (Ota and Nakayama, 1970), (2) the development

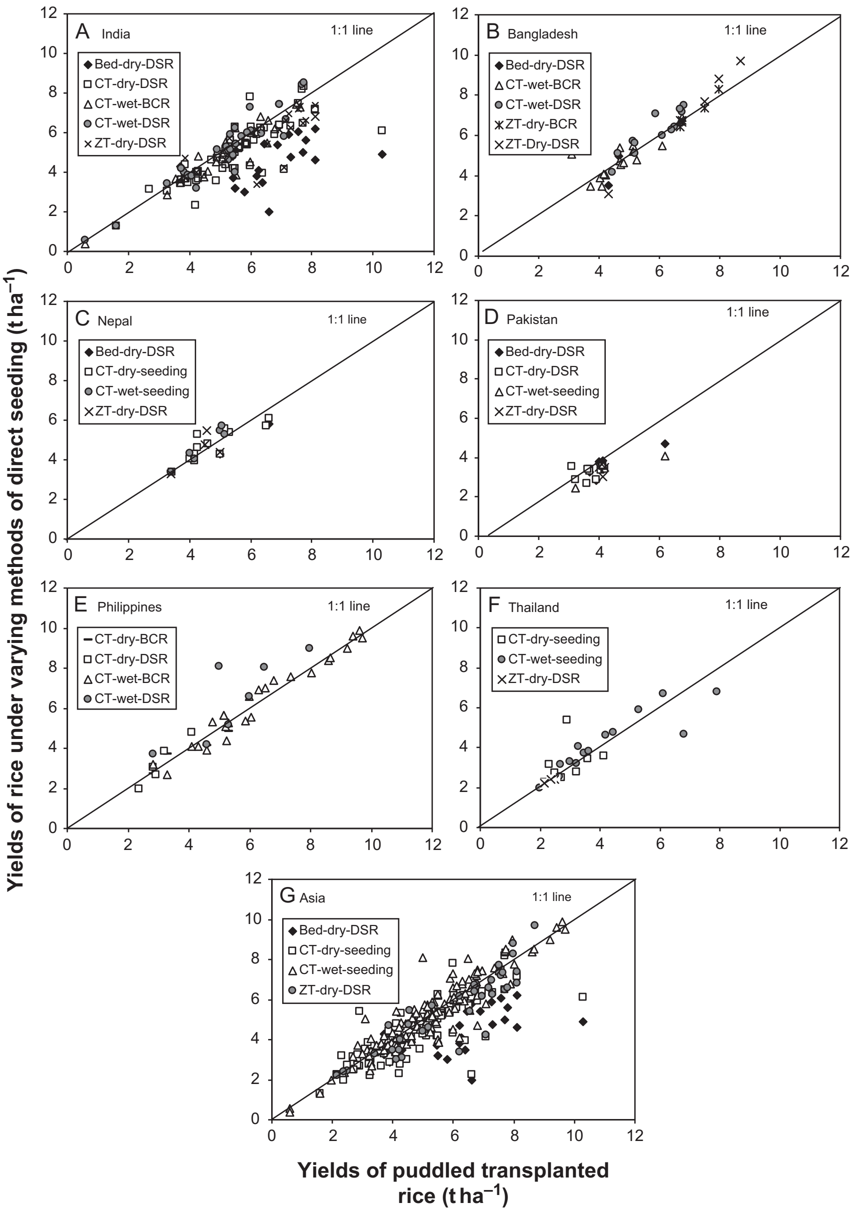

Figure 7 Rice grain yield of puddled transplanted rice versus alternative tillage and rice establishment (CE) methods from researcher-managed on-station and on-farm trials: (A) India, (B) Bangladesh, (C) Nepal, (D) Pakistan, (E) Philippines, (F) Thailand, and (G) Asia (overall of all six countries). See Table 5 for details of tillage and CE methods.

of new-generation precise seeding and land-leveling machinery for dry drill seeding (Gopal *et al.*, 2010; Gupta *et al.*, 2006; Rickman, 2002), (3) integrated weed management (IWM), including the use of effective herbicides and nonchemical methods for weed control (Chauhan and Johnson, 2010; Rao *et al.*, 2007; Singh *et al.*, 2009b), and (4) breeding more lodging-tolerant genotypes and using of hill seeding or row seeding instead of broadcasting to minimize lodging (Yoshinaga, 2005).

5.2. Irrigation water application and irrigation water productivity

A review of 44 studies (36 researchers-managed and 8 farmers-managed) from different countries showed 12–33% (139–474 mm) lower irrigation water use in DSR than in flooded CT-TPR (Table 8). The reduction in irrigation water use varied with type of DSR method, ranging from 139 mm (12%) in wet seeding on puddled soil (CT-wet-seeding) to 304–385 mm (21–25%) in dry seeding after tillage (CT-dry-seeding) or zero tillage (ZT-dry-seeding), and 474 mm (33%) in dry seeding on raised beds (Bed-dry-DSR).

Table 8 Analysis of irrigation water application comparisons between puddled transplanting and various alternative tillage and crop establishment methods

Tillage and CE methods[a]	N[b]	Adjusted mean of irrigation water use (mm)[c]	Change from CT-TPR (mm)[d]	P value[e]	% Change
CT-TPR	44	1372	–	–	–
CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	27	1234	−139	0.0307	−12
CT-dry-seeding (CT-dry-BCR, CT-dry-DSR)	31	1074	−304	0.001	−21
Bed-dry-DSR	14	887.5	−474	0.001	−33
ZT-dry-seeding (ZT-dry-BCR, ZT-dry-DSR)	6	1039	−385	0.001	−25

[a] Refer to Table 5 for a description of tillage and CE methods.
[b] Number of studies.
[c] Adjusted mean of irrigation water calculated using SAS mixed model analysis.
[d] Adjusted mean of change in irrigation water application over CT-TPR calculated using SAS mixed model analysis.
[e] Based on analysis of change data (pair comparison with CT-TPR).

The relatively lower water use in Wet-DSR than in CT-TPR despite its longer main field duration may be because of fewer continuous flooded days in the main field (Fig. 8A and B). In CT-TPR, the field is generally kept continuously flooded (Fig. 8A). Whereas in Wet-DSR, during the first 10 days, very little or no irrigation is applied and then irrigation is either applied at 2- to 3-day intervals or relatively shallow flooding is maintained during the early part of vegetative growth to avoid submergence of young seedlings, thereby reducing seepage, percolation, and evaporation losses. Moreover, the Wet-DSR crop is harvested about 10–15 days earlier than CT-TPR; therefore, total duration from seed to seed is reduced in this method (Fig. 8B). Another reason reported for lower water use in Wet-DSR is the shorter land preparation period than in CT-TPR. In some areas, for example, in the largest surface irrigation scheme in Central Luzon, called UPRIIS (Upper Pampanga River Integrated Irrigation System), because of a lack of tertiary field channels, the whole main field is soaked when the nursery is prepared and kept flooded during the entire duration of the nursery for CT-TPR. This results in a longer land preparation period and higher seepage, percolation, and evaporation losses (Tabbal *et al.*, 2002). In Wet-DSR, the main field is soaked, and the land is prepared 2–3 days prior to sowing. In Dry-DSR, lower water use than that in CT-TPR may be attributed to savings in water used for puddling in CT-TPR and the AWD irrigation method instead of continuous flooding in CT-TPR (Fig. 8C).

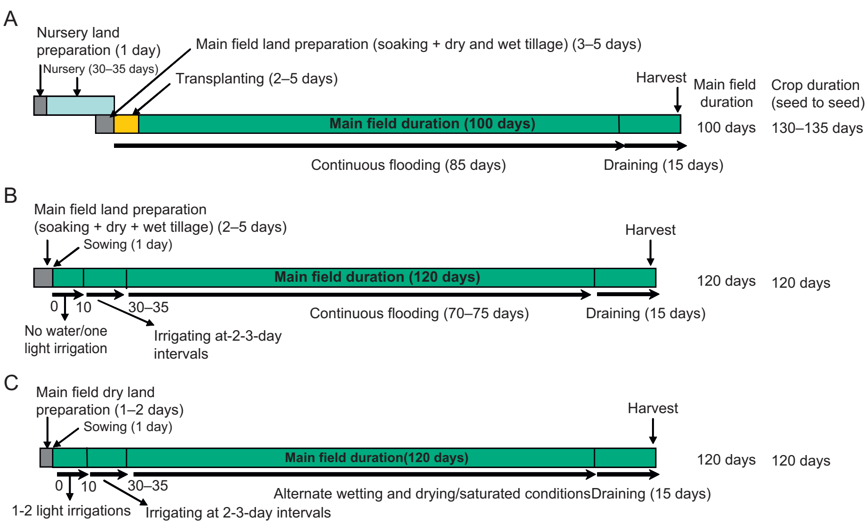

Figure 8 Various cultural activities, including irrigation schedules of puddled transplanting (A), direct wet seeding (B), and direct dry seeding (C). Modified from Tabbal *et al.* (2002).

Although the overall trend is a savings in irrigation water application with alternative tillage and methods of rice establishment, some authors have reported higher irrigation water use (Bhuiyan *et al.*, 1995; Hukkeri and Sharma, 1980), which could be due to (1) a longer crop growth period in the main field in DSR (Wet- and Dry-DSR) than in CT-TPR (Rashid *et al.*, 2009; Fig. 8), and (2) higher percolation losses, especially with Dry-DSR (Sudhir-Yadav *et al.*, 2011a,b). Rainfall pattern and time of occurrence are another major deciding factor in irrigation water use and resulting savings (Bhushan *et al.*, 2007; Saharawat *et al.*, 2010). If the onset of rain coincides with puddling and extends for a few days after CE, then irrigation water use declines drastically. Bhushan *et al.* (2007) and Gathala *et al.* (2011) highlighted savings in irrigation water use in years with favorable and unfavorable rainfalls. There is a trade-off between savings of irrigation water during land preparation and increased water use during crop growth, which is highly influenced by rainfall pattern.

Although all the DSR methods (wet or dry) were effective in saving irrigation water, their water use productivity (grain yield per liter of water applied) was higher only for wet seeding (CT-wet-seeding) and dry seeding on tilled soil (CT/RT-dry-seeding) (Fig. 9). However, irrigation water productivity in dry seeding on raised beds (Bed-dry-DSR) and zero-till (ZT-dry-DSR) was similar to that of CT-TPR due to lower yields in these systems. Bouman and Tuong (2001) also observed that most of the water-saving technologies, including DSR, result in some yield losses. Therefore, water productivity is a better indicator for making a comparison of different technologies in terms of their effective use of irrigation water and food production (Molden, 1997; Tuong, 1999). The results suggest that, to have a significant impact on irrigation water savings, yields of Bed-dry-DSR and ZT-dry-DSR should be further improved. There is also an urgent need to

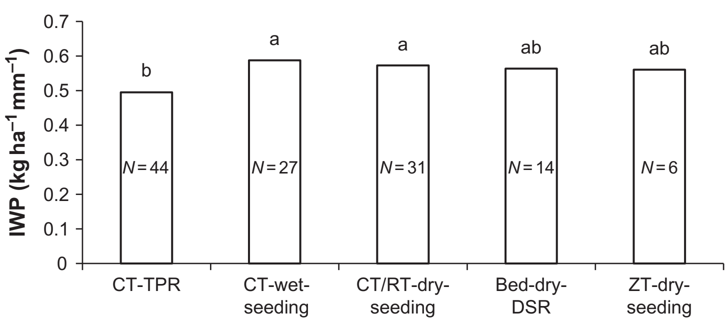

Figure 9 Irrigation water productivity (IWP) of major tillage and crop establishment methods in rice. See Table 5 for treatment details. *N* is the number of studies. Values followed by the same letter are not significantly different from each other at $P < 0.05$ by the Tukey test.

develop efficient irrigation schedules for the selected alternative tillage and rice establishment methods such as Dry-DSR. Irrigation scheduling should take various components of water and nutrient balance, and weed dynamics, into consideration.

5.3. Labor use

Compared with CT-TPR, DSR is a labor-saving technology. Large variations in total labor requirement for various field operations for diverse practices were reported (Table 9), which may largely be due to differences in the level of mechanization used. Depending on the method of land preparation and CE, the labor requirement in DSR can be up to 60% lower, with an average savings of 27% compared with CT-TPR. In Wet-DSR, labor savings ranged from none to 46%, with an average of 25%, whereas in Dry-DSR, savings ranged from 4% to 60%, with an average of 29%. The variation reported by different studies in labor savings primarily depends on labor used in weed control. Labor use is higher (12–200%) for controlling weeds in DSR than in CT-TPR. If weeds are controlled effectively with herbicides, the labor savings can be substantial.

Direct seeding (both wet and dry) avoids nursery raising, seedling uprooting, and transplanting, and thus reduces the labor requirement. Dry-DSR also avoids puddling operations, and thus further saves labor use. Since land preparation is mostly mechanized, there is more savings in machine labor than in human labor in this operation. Short- to medium-term on-station studies reported 34–46% savings in machine labor requirement in ZT-dry-DSR compared with CT-TPR (Bhushan *et al.*, 2007; Saharawat *et al.*, 2010).

In addition to labor savings, the demand for labor is spread out over a longer period in DSR than in transplanted rice. Conventional practice (CT-TPR) requires much labor in the critical operation of transplanting, which often results in a shortage of labor. The spread-out labor requirement helps in making full use of family labor and having less dependence on hired labor.

5.4. Economics

A major reason for farmers' interest in DSR is the rising cost of cultivation and decreasing profits with conventional practice (CT-TPR). Farmers likely prefer a technology that gives higher profit despite similar or slightly lower yield. Overall analysis of 77 published studies shows that various methods of direct seeding reduced the cost of production by US$9–125 ha^{-1} compared with conventional practice (CT-TPR) (Table 10). The largest reductions in cost occurred in practices in which reduced or zero tillage was combined with Dry-DSR. These cost reductions were largely due to either reduced labor cost or tillage cost or both under DSR

Table 9 Labor use (person-days ha^{-1}) in different field operations for direct-seeded and transplanted rice

S. no.	Country	Tillage and CE method[a]	Labor use (person-days ha^{-1}) Nursery	Seedling uprooting	Land preparation	Crop establishment (sowing/transplanting)	Weeding	Harvesting/ threshing	Total	% saving	Reference
1	Bangladesh	CT-TPR	14	11	5	28	34	39	139	0	Rahman *et al.* (2008)
		CT-wet-BCR	0	0	6	2	54	50	121	13	
2	Bangladesh	CT-TPR	2	10	–[b]	27	34	32	118	0	Rashid *et al.* (2009)
		CT-wet-DSR (drum)	0	0	–	1	38	36	92	23	
3	India	CT-TPR	24[c]		–	22	20	–	109	0	Ramasamy *et al.* (2006)
		CT-wet-BCR	0[c]b		–	1	25	–	69	37	
4	India	CT-TPR	5	–	–	75	30	–	229	0	Thakur *et al.* (2004)
		CT-wet-BCR	0	–	–	3	90	–	186	19	
		CT-wet-DSR (line sown)	0	–	–	20	40	–	214	7	
		CT-dry-BCR	0	–	–	2	100	–	220	4	
5	India	CT-TPR	–	–	–	–	–	–	66	0	Bhushan *et al.* (2007)
		Bed-dry-DSR	–	–	–	–	–	–	47	29	
		ZT-dry-DSR	–	–	–	–	–	–	47	28	
6	India	CT-TPR	–	–	–	–	–	–	64	0	Saharawat *et al.* (2010)
		CT-wet-SR (drum)	–	–	–	–	–	–	67	0	
		ZT-dry-DSR	–	–	–	–	–	–	56	13	
7	Korea	CT-TPR (machine)	–	–	–	-	–	–	42	0	Lee *et al.* (2002)
		CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	–	–	–	–	–	–	31	27	
		CT-dry-seeding	–	–	–	–	–	–	29	31	
8	Malaysia	CT-TPR	–	–	–	–	–	–	237	0	Wong and Morooka (1996)
		CT-wet-BCR	–	–	–	–	–	–	80	66	
9	Philippines	CT-TPR	–	–	–	–	–	–	53		Pandey and Velasco (1998)
		CT-wet-seeding (CT-wet-BCR, CR-wet-DSR)	–	–	–	–	–	–	30	40	
		CT-dry-seeding (CT-dry-BCR, CT-dry-DSR)	–	–	–	–	–	–	40	20	

(*Continued*)

Table 9 (*Continued*)

S. no.	Country	Tillage and CE method[a]	Labor use (person-days ha^{-1}) Nursery	Seedling uprooting	Land preparation	Crop establishment (sowing/transplanting)	Weeding	Harvesting/ threshing	Total	% saving	Reference
10	Philippines	CT-TPR	3	4	10	22	–	–	97	0	Tisch and Paris (1994)
		CT-wet-BCR	0	0	10	2	–	–	49	49	
11	Philippines	CT-TPR	–	–	–	–	–	–	49	0	Pandey *et al.* (1995)
		CT-dry-seeding (CT-dry-BCR, CT-dry-DSR)	–	–	–	–	–	–	22	60	
12	Thailand	CT-TPR	2	–	6	23	3	29	65	0	Sumita and Ando (2001)
		CT-dry-BCR	0	–	4	3	1	28	40	39	
13	Thailand	CT-TPR	–	–	4	15	–	–	39	0	Isvilanonda (2002)
		CT-wet-BCR	–	–	3	2	–	–	30	24	
14	Thailand	CT-TPR	–	–	–	–	–	–	74	0	Pandey *et al.* (2002)
		CT-wet-BCR	–	–	–	–	–	–	40	46	
15	Vietnam	CT-TPR	–	–	–	–	–	–	68	0	Pandey *et al.* (2002)
		CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	–	–	–	–	–	–	38	40	
		CT-dry-seeding (CT-dry-BCR, CT-dry-DSR)	–	–	–	–	–	–	38	40	

[a] Refer to Table 5 for a description of tillage and CE methods.
[b] Data not available.
[c] This is sum of labor used in nursery raising and seedling uprooting.

Table 10 Analysis of cost of production and net income comparisons between puddled transplanting and various alternative tillage and crop establishment methods in Asia

Country	Tillage and CE method[a]	N[b]	Total cost (US$ ha^{-1})[c]	Δ cost (US $ ha^{-1})[d]	*P* value[e]	*N*[c]	Net income (US$ ha^{-1})[f]	Δ NI (US $ ha^{-1})[g]	*P* value[h]
India	CT-TPR	15	397	–	–	35	277	–	–
	CT-wet-BCR	3	365	−26	NS	7	265	−6	NS
	CT-wet-DSR	3	357	−31	NS	17	322	35	0.1100
	CT-dry-DSR	13	352	−48	0.0143	21	281	8	NS
	Bed-dry-DSR	3	283	−120	0.0002	7	130	−166	<0.0001
	ZT-dry-DSR	3	277	−125	0.0002	8	308	1	NS
Bangladesh	CT-TPR	10	409	–	–	11	475	–	–
	CT-wet-BCR	3	395	−13.0	NS	5	493	27	0.070
	CT-wet-DSR	5	390	−9.0	NS	6	552	74	0.0001
	ZT-dry-BCR	3	380	−44.0	0.0006	4	495	13	NS
	ZT-dry-DSR	4	384	−40.0	0.0013	4	535	52	0.0033
Nepal	CT-TPR	5	212	–	–	5	419	–	–
	CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	5	180	−34	0.0927	3	500	89	0.0722
	CT/RT-dry-DSR-Flat	3	176	−39	0.0361	5	496	81	0.0436
Philippines	CT-TPR	12	408	–	–	12	362	–	–
	CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	9	429	8	NS	9	498	132	0.0022
	CT-dry-seeding (CT-dry-BCR, CT-dry-DSR)	7	380	−25	0.0532	7	449	94	0.0218
Thailand	CT-TPR	12	288	–	–	12	60	–	–
	CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	12	256	−32	0.0004	12	117	58	0.0043

(Continued)

Table 10 (*Continued*)

Country	Tillage and CE method[a]	N[b]	Total cost (US$ ha^{-1})[c]	Δ cost (US $ ha^{-1})[d]	*P* value[e]	*N*[c]	Net income (US$ ha^{-1})[f]	Δ NI (US $ ha^{-1})[g]	*P* value[h]
Asia	CT-TPR	57	359	–	–	77	286	–	–
	CT-wet-seeding (CT-wet-BCR, CT-wet-DSR)	40	338	−22	0.0259	61	338	51	0.0115
	CT/RT-dry-seeding (CT/RT-dry-BCR, CT/RT-dry-DSR)	28	324	−29	0.0084	36	314	30	0.0619
	Bed-dry-DSR	8	301	−58	0.0002	12	221	−62	0.0003
	ZT-dry-seeding (ZT-dry-BCR, ZT-dry-DSR)	11	294	−80	<0.0001	18	337	51	0.0197

[a] Refer to Table 5 for a description of tillage and CE methods.
[b] Number of studies.
[c] Adjusted mean of production cost calculated using SAS mixed model analysis.
[d] Adjusted mean of change in production cost over CT-TPR calculated using SAS mixed model analysis.
[e] Based on analysis of change data (Δ cost) (pair comparison with CT-TPR).
[f] Adjusted mean of net income calculated using SAS mixed model analysis.
[g] Adjusted change in net income over CT-TPR using SAS mixed model analysis.
[h] Based on analysis of change data (Δ net income) (pair comparison with CT-TPR).

systems. In regions where wages are high (e.g., Haryana and Punjab states of India), the labor cost savings in rice establishment can reach US$50 ha^{-1} (Kumar *et al.*, 2009).

However, these reduced costs did not always translate into increased profitability. For example, the cost of growing rice on raised beds in India was the lowest among different alternative tillage and CE methods but there was a net loss of returns of US$166 ha^{-1} compared with CT-TPR, which was primarily due to associated lower grain yield. Increases in net returns in other direct-seeding methods compared to CT-TPR were highly variable, ranging from US$1 to 132 ha^{-1} primarily because of large yield variability. On average, the increases in net returns with direct-seeding on puddled or zero-till soil were similar (US$51 ha^{-1}). Overall, all types of direct-seeding methods, except Bed-dry-DSR, were either more profitable than or equally profitable as puddled transplanted rice.

The labor and water costs are likely to increase in future which will make DSR economically more attractive to the farmers.

5.5. Greenhouse gas (GHG) emissions

Agricultural practices play an important role in the emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—three important GHGs that contribute to global warming. Agriculture's share in the total emissions of N_2O, CH_4, and CO_2 are 60%, 39%, and 1%, respectively (OECD, 2000), with rice-based cropping systems playing a major role. Rice production systems impact global warming potential (GWP) primarily through effects on methane, but N_2O and CO_2 effects can also be important in some systems. The GWP of CH_4 and N_2O is 25 and 298 times higher than that of CO_2 (IPCC, 2007). GHG emissions, especially CO_2 and CH_4 from rice fields, are large and very sensitive to management practices. Therefore, rice is an important target for mitigating GHG emissions (Wassmann *et al.*, 2004). Flooded rice culture with puddling and transplanting is considered one of the major sources of CH_4 emissions because of prolonged flooding resulting in an anaerobic soil condition. It accounts for 10–20% (50–100 Tg $year^{-1}$) of total global annual CH_4 emissions (Houghton *et al.*, 1996; Reiner and Milkha, 2000).

Studies comparing CH_4 emissions from different tillage and CE methods but with similar water management (continuous flooding/mid-season drainage/intermittent irrigation) in rice revealed that, except in one study (Setyanto *et al.*, 2000), CH_4 emissions were lower with Wet- or Dry-DSR than with CT-TPR (Table 11). The reported reduction in CH_4 emissions was higher in Dry-DSR than in Wet-DSR. Under continuous flooding, the reduction in CH_4 emissions ranged from 24% to 79% in Dry-DSR and from 8% to 22% in Wet-DSR, whereas, under intermittent irrigation, the reduction ranged from 43% to 75% in Dry-DSR compared with CT-TPR. However, when DSR was combined with mid-season drainage or

Table 11 Effects of various tillage and crop establishment methods on methane emissions in Asia

S. no.	Location/ country	Year/season	Tillage and crop establishment method	Water management	Seasonal total emission (kg CH_4 ha^{-1})	% change from TPR or puddling	Yield (t ha^{-1})	Reference
1	Beijing	1991	CT-TPR	Intermittent irrigation	299	0	4.5	Wang *et al.* (1999)
			CT-dry-seeding	Intermittent irrigation	74	−75	3.6	
2	Southeastern Korea	1996	CT-TPR (30-day-old seedling)	Continuous flooding	403	0	5.3	Ko and Kang (2000)
			CT-TPR (8-day-old seeding)	Continuous flooding	424	5	5.4	
			CT-wet-seeding	Continuous flooding	371	−8	5.4	
			CT-dry-seeding	Continuous flooding	269	−33	5.3	
3	Milyang, Korea	1998–2000	CT-TPR	Continuous flooding	402	0	–	Ko *et al.* (2002)
			CT-dry-seeding	Continuous flooding	241	−40	-	
			ZT-dry-TPR	Continuous flooding	295	−27		
			ZT-dry-seeding	Continuous flooding	258	−36		

4	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	Rainfed	59	0	4.9	Setyanto *et al.* (2000)
			CT-dry-seeding	Rainfed	26	−56	4.4	
5	Akasaka, Japan	1992–1994	CT-TPR	Continuous flooding	159	0	–	Ishibashi *et al.* (2001)
			ZT-dry-seeding	Continuous flooding	34	−79	–	
	Suimon, Japan	1994–1997	CT-TPR	Continuous flooding	271	0	–	Ishibashi *et al.* (2001)
			ZT-dry-seeding	Continuous flooding	129	−52	–	
6	Sanyoh, Japan	1992-2000	TPR	Continuous flooding	330	0	–	Tsuruta (2002)
			ZT-dry-DSR	Continuous flooding	252	−24	–	
7	Hachirogata polder, Japan	2004–2005	CT-TPR	Intermittent irrigation	179	0	5.4	Harada *et al.* (2007)
			Unpuddled (CT-dry)-TPR	Intermittent irrigation	182	2 ns	5.6	
			ZT-dry-TPR[a]	Intermittent irrigation	102	−43	5.5	

(*Continued*)

Table 11 (*Continued*)

S. no.	Location/ country	Year/season	Tillage and crop establishment method	Water management	Seasonal total emission (kg CH_4 ha^{-1})	% change from TPR or puddling	Yield (t ha^{-1})	Reference
8	Maligaya, Philippines	1997 DS	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	Corton *et al.* (2000)
			CT-wet-DSR	Midseason drainage	48	−6	6.4	
		1997 WS	CT-TPR	Continuous flooding	348	0	5.4	Corton *et al.* (2000)
			CT-wet-DSR	Continuous flooding	272	−22	3.5	
			CT-TPR	Midseason drainage	323	0	5.5	Corton *et al.* (2000)
			CT-wet-DSR	Midseason drainage	150	−54	3.4	
		1998 DS	CT-TPR	Continuous flooding	90	0	8.5	Corton *et al.* (2000)
			CT-wet-DSR	Midseason drainage	16	−82	7.7	
			CT-wet-DSR	Intermittent irrigation	7	−92	7.1	

9	Pantnagar, India	2004	CT-TPR	–	315	0	6.8	Singh *et al.* (2009a)
			CT-dry-DSR	–	220	−30	6.6	
10	Karnal, India[b]	2006–2007	CT-TPR	–	59	0	–	Saharawat (unpublished)
			CT-dry-DSR	–	25	−58	–	
11	Modipuram, India[b]	2000–2005	CT-TPR	–	60	0	–	Pathak *et al.* (2009)
			CT-dry-DSR	–	25	−58	–	

Refer to Table 5 for a description of tillage and CE methods.

[a] In all treatments (zero tillage, no puddling, and puddling), rice was transplanted.

[b] Values are based on simulation modeling.

intermittent irrigation, the reduction in CH_4 emissions increased further compared with flooded CT-TPR. For example, in Wet-DSR, the reduction in CH_4 increased from 16%–22% (under continuous flooding) to 82%–92% (under mid-season drainage or intermittent irrigation) compared with CT-TPR under continuous flooding (Corton *et al.*, 2000; Table 11). Wassmann *et al.* (2004) also suggested that CH_4 mitigation effects can be further enhanced if Wet- or Dry-DSR is combined with mid-season drainage.

CH_4 emissions even in CT-TPR vary considerably from study to study (Table 11). This difference could be because of individual or combined effects of different soil characteristics, climatic conditions, and management such as soil pH, redox potential, soil texture, soil salinity, temperature, rainfall, and water management (Aulakh *et al.*, 2001). The reason for low CH_4 emissions from Dry-DSR is aerobic conditions, especially during the early growth stage. Even under Wet-DSR, field is kept aerobic until seedlings are established. Anaerobic conditions are a prerequisite for the activities of methanogenic bacteria and CH_4 production. 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; Wang *et al.*, 1993).

Although water-saving technologies including Dry-DSR can reduce CH_4 emissions, relatively more soil aerobic states can also increase N_2O emissions. Nitrous oxide production increases at redox potentials above 250 mV (Hou *et al.*, 2000). In a study conducted in India comparing N_2O emissions from CT-TPR and different Dry-DSR methods (CT-dry-DSR, Bed-dry-DSR, ZT-dry-DSR), it was found that N_2O emissions were 0.31–0.39 kg N ha^{-1} in CT-TPR, which increased to 0.90–1.1 kg N ha^{-1} in CT-dry-DSR and Bed-dry-DSR and 1.3–2.2 kg N ha^{-1} in ZT-dry-DSR (Fig. 10). Similarly, a study conducted by Ishibashi *et al.* (2007) in western Japan also observed higher emissions of N_2O under ZT-dry-DSR than in CT-TPR. These results suggest the need to deploy strategies to reduce N_2O emissions from Dry-DSR for minimizing adverse impacts on the environment. Hou *et al.* (2000) suggested developing water management practices in such a way that soil redox potential can be kept at intermediate range (-100 to $+200$ mV) to minimize emissions of both CH_4 and N_2O. This range is high enough to prevent CH_4 production and low enough to encourage N_2O reduction to N_2 as the critical soil redox potential identified for N_2O production is $+250$ mV (Hou *et al.*, 2000).

An overall effect of direct-seeding methods on GWP depends on total emissions of all three major GHGs. It has been observed that measures to reduce one source of GHG emissions often lead to increases in other GHG emissions, and this trade-off between CH_4 and N_2O is a major hurdle in devising an effective GHG mitigation strategy for rice (Wassmann *et al.*, 2004). Very few studies have compared different rice production systems in

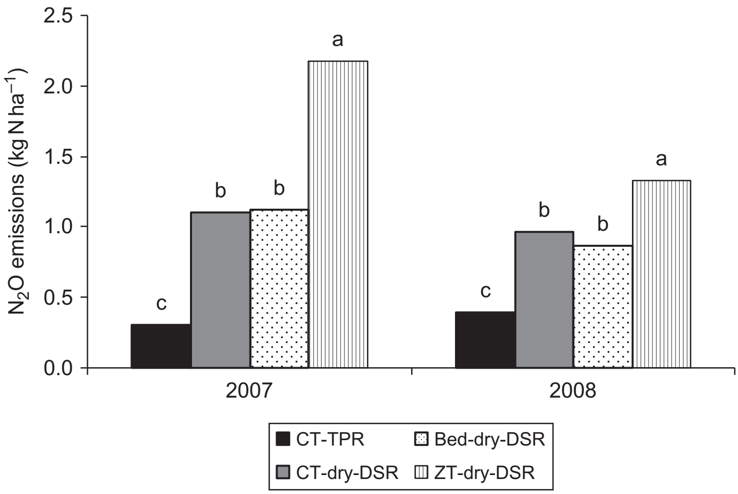

Figure 10 Nitrous oxide emission from puddled transplanted rice and methods of alternate tillage and crop establishment in 2007 and 2008 at Modipuram in India. Within years, means with the same letters are not significantly different at the 0.05 level by the Tukey test. See Table 5 for details of tillage and crop establishment methods. Source: Sharma *et al.* (unpublished).

terms of total GWP taking into account all three GHGs. Ishibashi *et al.* (2009) compared ZT-dry-DSR with CT-TPR and found ZT-dry-DSR 20% more efficient in reducing GWP. Pathak *et al.* (2009) simulated for Indian conditions and found that Dry-DSR on raised beds or ZT has potential to reduce CO_2 equivalent ha^{-1} by 40–44% compared with CT-TPR. Harada *et al.* (2007) reported that, just by changing puddling to zero tillage, GWP declined by 42% in Japan.

In summary, despite relatively higher emissions of N_2O in Dry-DSR, GWP of Dry-DSR tends to be lower than for flooded CT-TPR because of substantially higher emissions of CH_4 in CT-TPR. However, more systematic studies involving simultaneous measurements of three GHGs are needed to come to sound conclusions. Further, considering the burgeoning global demand for food, fiber, and fuel, appropriate GHG emission strategies must involve ecologically intensive crop management practices that enhance nutrient use efficiency and maintain high yields (Cassman, 1999).

6. Potential Benefits and Risks Associated with Direct-Seeded Rice

Direct-seeding of rice has the potential to provide several benefits to farmers and the environment over conventional practices of puddling and transplanting. However, it is also important to understand and predict

Table 12 Benefits and risks/limitations associated with direct seeding of rice

A.	Benefit
1.	Labor savings ranged from 0% to 46%, with an average of 25% in wet direct seeding and 4% to 60%, with an average of 29%, in dry direct seeding
2.	Reduces drudgery by eliminating transplanting operation
3.	Water savings ranged from 12% to 35% depending on type of DSR. Water savings in different types of DSR ranked in the following order: CT-wet-seeding < CT-dry-seeding = ZT-dry-DSR < Bed-dry-DSR
4.	Reduces irrigation water loss through percolation due to fewer soil cracks
5.	Reduces methane emissions (6–92% depending on types of DSR and water management)
6.	Reduces cost of cultivation, ranging from 2% to 16% (US$8–34 ha^{-1}) in wet DSR and from 6% to 32% (US$29-125 ha^{-1}) in Dry-DSR
7.	Increases the total income of farmers (US$30–51 ha^{-1} depending on type of DSR)
8.	Allows timely planting of subsequent crop due to early harvest of direct-seeded rice crop by 7–14 days
B.	Risk
1.	Sudden rain immediately after seeding can adversely affect crop establishment
2.	Reduces availability of soil nutrients such as N, Fe, and Zn especially in Dry-DSR
3.	Appearance of new weeds such as weedy or red rice
4.	Increases dependence on herbicides
5.	Increases incidence of new soil-borne pests and diseases such as nematodes
6.	Enhances nitrous oxide emissions from soil
7.	Relatively more soil C loss due to frequent wetting and drying

possible risks or threats that direct seeding may have in the long run. Table 12 summarizes these benefits and risks.

7. Weeds in Direct-Seeded Rice: A Major Constraint

Weeds are a major constraint to the success of DSR in general and to Dry-DSR in particular (Johnson and Mortimer, 2005; Rao *et al*., 2007; Singh *et al*., 2006). Research has shown that, in the absence of effective weed control options, yield losses are greater in DSR than in transplanted rice (Baltazar and De Datta, 1992; Rao *et al*. 2007). Weeds are more problematic in DSR than in puddled transplanting because (1) emerging DSR seedlings are less competitive with concurrently emerging weeds and (2) the initial flush of weeds is not controlled by flooding in Wet- and Dry-DSR (Kumar *et al*., 2008a; Rao *et al*., 2007).

It is important to review the weed-related issues emerging with the adoption of DSR based on the experiences from those countries where transplanting is being replaced widely by DSR. This would assist in developing effective and economically viable medium- to long-term sustainable weed control strategies. This section reviews some of the weed related issues that have emerged in countries where DSR is widely practiced.

7.1. Evolution of weedy rice

Weedy rice (*O. sativa* f. *spontanea*), also known as red rice, has emerged as a serious threat to rice production in areas where transplanting is widely replaced by direct seeding, especially in many Asian countries. Table 13 describes the evolution of weedy rice and its key characteristics in relation to the adoption of DSR.

Weedy rice is highly competitive and causes severe rice yield losses ranging from 15% to 100% (Table 13). Weedy rice densities of 4, 16, and 25 m^{-2} reduced rice yield by 13%, 37%, and 48%, respectively (Pantone and Baker, 1991). Other studies reported up to a 58% reduction in rice yield at a density of 40 weeds m^{-2} (Eleftherohorinos *et al.*, 2002) and up to 82% at a density of 215 weeds m^{-2} (Diarra *et al.*, 1985). Smith (1988) reported a density of 1–3 plants m^{-2} as the threshold level for control to avoid yield loss. Weedy rice also reduces milling quality if it gets mixed with rice seeds during harvesting (Ottis *et al.*, 2005).

Weedy rice is difficult to control because of its genetic, morphological, and phenological similarities with rice. Selective control of weedy rice was never achieved at a satisfactory level with herbicides (Noldin *et al.*, 1999a,b). In Malaysia, proper land preparation coupled with the stale seedbed technique using nonselective herbicides (paraquat/glyphosate/glufosinate) before planting rice has been recommended to reduce the density of weedy rice (Karim *et al.*, 2004). FAO (1999) recommends an integrated approach that combines preventive, cultural, and chemical methods. The keys for control and to avoid further infestation are to use clean and certified seeds (Rao *et al.*, 2007). Azmi and Abdullah (1998) observed that preplant application of soil-incorporated molinate at 4.5 kg ai ha^{-1} was effective in reducing the seed bank of weedy rice. Herbicide-resistant rice technologies offer opportunities for selective control of weedy rice but the risk of gene flow from herbicide-resistant rice to weedy rice poses a constraint for the long-term utility of this technology (Kumar *et al.*, 2008b).

Weedy/red rice could become a major threat to rice production where Dry-DSR replaces CT-TPR. Therefore, there is a need to develop preventive management strategies to deal with the weedy-rice problem in Dry-DSR.

Table 13 Emergence of weedy rice in Asian countries where direct seeding is predominant

Country	DSR introduction year	DSR area (% of total rice area)	Weedy rice first detection year	Rice grain yield losses due to weedy rice	Current status of weedy rice
Korea	1991[a]	In 1995, it was 11% and decreased to 4.5% in 2007[b]	NA	NA	Major constraint with up to 35% infestation in mostly Dry-DSR[b]
Malaysia	Late 1970s or early 1980s[c]	>95[d]	1988[e]	Up to 74% in heavily infested areas[f,g]	Serious infestation of weedy rice observed after 20 consecutive seasons of direct seeding.[h] In Muda area, almost all fields infested with weedy rice[i]; 10% is heavily infested.[j] A similar situation is also reported in other Malaysian irrigation schemes[i,k]

Sri Lanka	NA	> 93[l]	1992[l]	30–100%[m]	In 2008, in Ampara and Puttalam districts, many farmers could not cultivate their fields because of weedy rice[l]
Thailand	1980s	34[n]	2001[o]	60–80%[p]	First detected at two locations in central Plain and now found in seven provinces of central and lower northern Thailand in about 3.0 million ha of area of direct-seeded rice[b]

(*Continued*)

Table 13 (*Continued*)

Country	DSR introduction year	DSR area (% of total rice area)	Weedy rice first detection year	Rice grain yield losses due to weedy rice	Current status of weedy rice
Vietnam	Early 1980s[q]	39–47[n]	1994[r]	15–70%[s]	Weedy rice is a major problem in Mekong Delta area in summer–autumn crops. In wet seeding, it is not a major problem[s,t]

NA, data not available.

[a] Kim and Ha (2005).
[b] Gressel and Valverde (2009).
[c] Azmi *et al*. (2005).
[d] Azmi (personal communication).
[e] Azmi and Abdullah (1998).
[f] Watanabe *et al*. (1996).
[g] Bakar *et al*. (2000).
[h] Ho (1996).
[i] Begum *et al*. (2005).
[j] Azmi and Baki (2007).
[k] Mispan and Baki (2008).
[l] Weerakoon *et al*. (2011).
[m] Gunawardana (2008).
[n] Pandey and Velasco (2002).
[o] Maneechote *et al*. (2004).
[p] Vongsaroj (2000).
[q] Can and Xuan (2002).
[r] Chin (1997).
[s] Chin (2001).
[t] Mai *et al*. (2000).

7.2. Changes in composition and diversity of weed flora and a shift toward more difficult-to-control weeds

Changes in rice establishment method as well as water, tillage, and weed management practices in DSR lead to changes in weed composition and diversity. Weed flora composition can change drastically with a shift from CT-TPR to some form of alternative tillage and rice establishment methods (Singh *et al.*, 2009b). Tomita *et al.* (2003) observed more species-rich vegetation and diverse weed flora in Dry-DSR than in CT-TPR. A total of 46 species were present in transplanted rice in 1989, and, after 3 years (six seasons of rice) of Wet-DSR, 21 new weed species were added to the weed flora (Azmi and Mashor, 1995; Mortimer and Hill, 1999). Kim *et al.* (1992) observed a diversity index of 0.118 in Korean CT-TPR compared with 0.317 in Dry-DSR. In a study conducted in Modipuram, India, Singh *et al.* (2009b) reported that the number of species of grasses, broadleaves, and sedges was 6, 4, and 4, respectively, in CT-TPR, whereas, in Dry-DSR, it increased to 15 grass species, 19 broadleaf species, and the number of sedge species remained unaffected. This clearly shows that some new grass and broadleaf species that were not adapted to CT-TPR appeared in Dry-DSR. Higher numbers and more diverse flora in Dry-DSR could result in lower efficacy of weed management strategies, including herbicides.

In addition, adopting DSR may result in weed flora shifts toward more difficult-to-control and competitive grasses and sedges. For example, in Malaysia, at the time of the introduction of direct seeding (Wet-DSR) in the 1970s, easy-to-control broadleaf weeds were dominant but, by the 1990s, grass species such as *Echinochloa crus-galli*, *Leptochloa chinensis* (L.) Nees, and *Ischaemum rugosum* Salisb. became dominant (Azmi *et al.*, 1993, Azmi *et al.*, 2005). Similar shifts in weed flora were reported by Ho and Itoh (1991) in Malaysia when rice crops shifted from CT-TPR to Dry- and Wet-DSR. In a long-term and more detailed field study conducted in Malaysia, weedy rice and *L. chinensis* were absent in Wet-DSR plots at the start of the experiment in 1989. However, *L. chinensis* appeared after only 2 years (in 1991) and weedy rice after 4 years (in 1993) of experimentation. By 2001, weedy rice, *Echinochloa* spp., *L. chinensis*, and *Fimbristylis miliacea* became the dominant species (Azmi and Mashor, 1995; Mortimer and Hill, 1999). In Vietnam also, shifts toward more difficult-to-control grass weed species (*E. crus-galli, L. chinensis*, and weedy rice) were observed with the introduction of DSR (Chin *et al.*, 2000). Vongsaroj (1997) reported dicotyledonous weeds as dominant in transplanted rice, but annual grasses such as *E. crus-galli* and *L. chinensis* and sedges such as *F. miliacea* in DSR fields in Vietnam. Similar shifts have also been reported in India. Singh *et al.* (2005) observed that *E. crus-galli, Commelina diffusa* Burm. f.*, Cyperus rotundus* L., *Cyperus iria*, and *L. chinensis* were dominant in non-weeded Dry-DSR plots in comparison with *C. iria*, *Echinochloa colona*, and *Caesulia* *axillaris* Roxb. in CT-TPR plots after four seasons of rice cropping. Direct seeding also favors sedges such as *Cyperus difformis*, *C. iria*, *C. rotundus*, and *F. miliacea* (Azmi and Mashor, 1995; Gressel, 2002; Mortimer and Hill, 1999; Yaduraju and Mishra, 2005).

Therefore, it is important that a systematic weed monitoring program be put in place along with the introduction of DSR. This would make it possible to develop adequate IWM strategies, including identification of new herbicides that are effective against a wide spectrum of weeds.

7.3. Evolution of herbicide resistance

In countries where DSR is widely adopted, herbicide use increased steadily, resulting in the appearance of resistance in weeds against certain herbicides (Table 14). For example, in Malaysia, the first case of herbicide resistance was reported in *F. miliacea* against 2,4-D in 1989. But, currently, the numbers of weed biotypes resistant to different herbicides have increased to 10. Similarly, in Thailand, Korea, and the Philippines, the number of herbicide-resistance cases in weeds increased from none before DSR introduction to 5, 10, and 3, respectively, after DSR introduction. Although no herbicide resistance case has yet been reported in South Asia, preventive measures should already be considered.

8. Breeding Cultivars for Direct-Seeded Rice

Almost no varietal selection and breeding efforts have been made for developing rice cultivars suitable for alternate tillage and establishment methods, especially in unpuddled or zero-tillage soil conditions with direct seeding (Dry-DSR) in Asia (Fukai, 2002; Lafitte *et al*., 2002). Currently, no varieties are available that are targeted for this environment though there have been successful breeding programs for direct-seeded rice in puddled conditions (Wet-DSR) (Wah, 1998; Weerakoon *et al*., 2011). On-station and on-farm trials involving the evaluation of Dry-DSR cultivation have used rice varieties/hybrids that are primarily bred for puddled transplanting. Therefore, one can argue that comparisons of crop performance of rice in Dry-DSR with CT-TPR varieties have been biased. Based on the constraint analysis discussed in the preceding section, a plant type for Dry-DSR should be different from one for CT-TPR. An ideal plant type should have traits to deal with problems associated with early CE, weed competition, spikelet sterility, and lodging. We discuss these traits in detail with an aim to identify a suitable plant type for unpuddled or zero-tillage soil conditions with direct seeding (Dry-DSR).

Table 14 Evolution of herbicide resistance in Asian countries where direct-seeded rice is predominant

Country	Year of first resistance case reported	Resistance cases before DSR introduction (no.)	Total resistant biotypes (no.)	Total resistant weed species (no.)	Resistant weed species and year of appearance
Korea	1998	0	10	8	*Monochoria korsakowii* (1998), *M. vaginalis* (1999), *Lindernia dubia* (2000), *Scirpus juncoides* var. *ohwianus* (2001), *C. difformis* (2002), *Sagittaria pygmaea* (2004), *E. oryzicola* (2002), *Scripus maritimus* (2006)
Malaysia	1989	0	10	7	*Fimbristylis miliacea* (1989), *Ischaemum rugosum* (1989), *Sphenoclea zeylanica* (1995), *Limnocharis flava* (1998), *Sagittaria guyanensis* (2000), *Bacopa rotundifolia* (2000, 2001), *Limnophila erecta* (2002)
Philippines	1983	0	3	2	*Sphenoclea zeylanica* (1983), *E. crus-galli* (2005)
Sri Lanka	1997	0	2	2	*E. crus-galli* (1997), *Ischaemum rugosum* (2004)
Thailand	1998	0	5	3	*E. crus-galli* (1998), *Sphenoclea zeylanica* (2000), *L. chinensis* (2002)

Sources: Compiled from Heap (2010) and Sangakkara *et al*. (2004).

8.1. Anaerobic germination and tolerance of early submergence

Because rice is mainly grown during the monsoon season, establishment of direct-seeded rice can be adversely affected by untimely extended rains immediately after sowing. Emergence is poor if continuous rain prevails immediately after sowing or because of the mortality of young seedlings caused by submergence (Ismail *et al*., 2009). Therefore, ability to germinate under anaerobic conditions and tolerance of early submergence are important for establishing a good crop (Ismail *et al*., 2009). This trait may help in weed suppression too in areas where water is available by allowing early flooding. Although it is known that submergence tolerance is often associated with lower yield, McKenzie *et al*. (1994) were able to combine both submergence tolerance and high yield.

8.2. Early vigor

Good seed quality and seedling vigor are desirable for optimal establishment of a DSR crop, and also for weed competitiveness (Redoña and Mackill, 1996). Seedling vigor is defined as the ability of a plant's aerial part to emerge rapidly from soil or water (Heydecker, 1960). Rapid germination, rapid shoot and root growth, and long mesocotyls and coleoptiles are important seedling vigor-related traits (Cui *et al*., 2002; Redoña and Mackill, 1996; Sasahara *et al*. 1986; Williams and Peterson, 1973). All these traits will favor seedling establishment in direct seeding. For example, rapid germination and rapid shoot development are likely to help in avoiding submergence stress. A longer mesocotyl will minimize sensitiveness to seeding depth in drill seeding and improve seedling establishment. The modern semi-dwarf cultivars have a short mesocotyl, and this is disadvantageous for good CE, especially when seeds are drilled deeper in the soil (Dilday *et al*., 1990; Fukai, 2002; Turner *et al*., 1982). In the absence of precise land leveling and precise seeding machinery, it is difficult to achieve precise placement of seeds at shallow depth. Therefore, a suboptimal sowing depth leads to poor CE. Moreover, in conservation tillage systems in which residue is mulched, emergence of the crop may be adversely affected because of short mesocotyl.

8.3. Crop competitiveness against weeds

This is one of the most important plant traits required for the success of DSR. As discussed earlier, weeds are a major constraint in DSR cultivation. The development of weed-competitive cultivars is an attractive low-cost strategy of an overall IWM program for both low- and high-input cropping systems (Cousens, 1996; Dingkuhn *et al.*, 1999), and the most efficient way of delivery to farmers (Caton *et al.*, 2003).

Cultivar differences in weed competitiveness have been reported in many crops, including rice (Chavez, 1989; Fischer *et al.*, 2001; Garrity *et al.*, 1992; Haefele *et al.*, 2004; Quintero, 1986). Cultivar–weed competitiveness has two components: weed tolerance and weed-suppressive ability (Jannink *et al.*, 2000; Zhao *et al.*, 2006). Weed tolerance is the ability of plants to maintain high yields despite weed competition, whereas weed-suppressive ability is the ability to suppress the growth of weeds through competition. Breeding for weed-suppressive ability is being advocated over weed tolerance because suppressing weed growth will reduce weed seed production and minimize contributions to the weed seed bank (Jannink *et al.*, 2000; Jordan, 1993).

Rice characteristics reported to be associated with weed competitiveness include (a) plant height together with early and rapid growth rate (Caton *et al.*, 2003; Garrity *et al.*, 1992), (b) higher tiller number (Fischer *et al.*, 1997), (c) droopy leaves (Dingkuhn *et al.*, 1999), (d) relatively high biomass accumulation at the early stage (Ni *et al.*, 2000), (e) high leaf area index (Dingkuhn *et al.*, 1999) and high specific leaf area (Audebert *et al.*, 1999; Dingkuhn *et al.*, 1999) during vegetative growth, (f) rapid canopy ground cover (Lotz *et al.*, 1995), and (g) early vigor (Zhao *et al.*, 2006). It is argued that the introduction of some of these traits in a variety may result in some yield loss (Dingkuhn *et al.*, 1999; Jennings and Jesus, 1968; Kawano *et al.*, 1974; Pérez de Vida *et al.*, 2006). However, it is also argued that the benefit of having these traits is likely to be higher than when not having them (Fischer *et al.*, 2001; Garrity *et al.*, 1992; Gibson *et al.*, 2003; Ni *et al.*, 2000; Zhao *et al.*, 2006).

Although tall plants are linked to weed competitiveness, they often have low yield potential and tend to lodge. Fischer *et al.* (1997) 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). Unlike an initial shock in transplanting that delays tillering, tillering does not seem to be a constraint in direct seeding. Therefore, tillering ability is not a primary trait for selection (Dingkuhn *et al.*, 1990; Fukai, 2002; Song *et al.*, 2009). In fact, Song *et al.* (2009) reported that excessive tillering at an early stage could result in reduced leaf biomass and photosynthesis at a later stage and eventually become one of the major reasons for lower yields. *Oryza glaberrima*, a cultivated rice with low yield potential, possessing the trait of droopy leaves with high specific leaf area, is very effective in weed suppression. Jones *et al.* (1997a,b) suggested that, if this trait is restricted to early growth and combined with the trait of erect leaves with low specific leaf area from *O. sativa*, this can be useful for direct seeding.

Dingkuhn *et al.* (1999) suggested that the trade-off between weed competitiveness and high yield potential can be reduced by expressing weed competitiveness traits at an early development stage only. Through path analysis, Pérez de Vida *et al.* (2006) found that (a) early growth and light-capturing traits followed by moderate growth rates before heading and (b) a vigorous grain-filling period (high rate of grain-filling and long grain-filling duration) are ideal for both weed competitiveness and high yield potential. Therefore, an ideal plant type with an ability to compete against weeds would have early seedling vigor with shoots to quickly spread and cover the ground during the vegetative stage. It is thought that these characteristics theoretically result in a high radiation extinction coefficient, leading to high light use efficiency, and eventually result in the suppression of weeds. Further, Jones *et al.* (1997a,b) and Dingkuhn *et al.* (1999) argued that 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.

8.4. High crop growth rate during the reproductive phase

A slower crop growth rate during the reproductive phase has been reported to be associated with poor spikelet fertility, which is a most commonly observed characteristic in direct seeding. Horie (2001) reported that crop growth rate during the 2-week period preceding full heading determines yield through effects on spikelet number, single-grain mass, and potential grain-filling. The rice plant enters the reproductive phase about 1 month before anthesis and generally differentiates excess spikelets depending on previous N uptake. Spikelets then degenerate during this 2-week period preceding full heading depending on the availability of carbohydrates (Matsushima, 1957; Wada, 1969). Kato and Katsura (2010) observed that the frequency of floret abortion was associated with biomass production during the reproductive phase. This suggests that, in order to achieve high panicle fertility, sink demand should be met by high canopy photosynthesis at pre-anthesis and high remobilization ability.

Causes of low crop growth rate during the reproductive phase in direct seeding may be attributed to (a) high biomass during the vegetative phase and thus more maintenance respiration, (b) low foliar N concentration, and (c) reduced canopy CO_2 assimilation rates (Dingkuhn *et al.*, 1992; Yoshida, 1981). The low growth rate during the reproductive phase of direct-seeded rice leads to its earlier senescence than transplanted rice (Dingkuhn *et al.*, 1991a,b). Thus, a plant type with erect leaves having low specific leaf area (higher biomass per unit area) and high chlorophyll content (Dingkuhn *et al.*, 1999), which is likely to increase the crop growth rate during the reproductive phase (Horie *et al.*, 2004) and prolong the ripening phase

(Dingkuhn *et al.*, 1991a,b), has desirable characteristics for direct seeding. Katsura *et al.* (2010) found higher yield in direct-seeded aerobic rice than in puddled transplanted rice because of high N accumulation during the ripening phase. Thus, the ability to enhance N uptake during the ripening phase, which is a prerequisite to enhancing canopy photosynthesis and assimilate supply, is equally important to be considered in a breeding program for direct seeding (San-oh *et al.*, 2004). In addition, direct-seeded rice cultivars must possess enhanced assimilate export ability from the vegetative parts to reproductive parts during the reproductive phase (Dingkuhn *et al.*, 1991a,b).

8.5. Modified panicle architecture

Direct seeding, especially under dry conditions, can have the risk of dry spell even under irrigated conditions, which could adversely affect spikelet formation and development. Grain number per unit area, an important variable, is highly influenced by genotype and environment interaction. More grains in the primary branch of the panicle together with apical-borne spikelets are a stable trait and not much influenced by environment. Hence, selecting a genotype with more primary branches per panicle with more contribution by the primary branch apical-borne spikelets can provide some buffering to overcome the adverse effects of a dry spell during the reproductive period, and low-input level of water and nutrients (C.K. Reddy personal communication).

8.6. Modified root system

There are visible differences in rooting pattern of direct-seeded or transplanted rice plants. Kato and Okami (2010) found lower root biomass in Dry-DSR than in CT-TPR owing to a reduction in root biomass in the surface soil (fewer adventitious roots). However, the ratio of deep root to total root biomass was higher in Dry-DSR. Vigorous growth of superficial roots has been linked with the better performance of high-yielding lowland-adapted cultivars (Morita and Yamazaki, 1993). Therefore, in addition to deeper roots, vigorous adventitious surface rooting would be beneficial to improving N and water uptake efficiencies, especially during reproductive growth. Roots also play an important role in cytokinin synthesis. Cytokinin synthesis is enhanced in plants with a well-developed root system or when the physiological activity of roots is high (Soejima *et al.*, 1992, 1995). The rate of leaf senescence is low in plants in which a large amount of cytokinin is transported from the roots to the shoot (Soejima, 1992, 1995).

8.7. Lodging resistance

Lodging under DSR can be relatively more problematic than in CT-TPR because of the higher seed rate in DSR and when DSR is broadcast/surface-seeded. Therefore, 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 (IRRI, 1994; Setter *et al.*, 1997).

8.8. Shorter-duration rice cultivars

Rice grain yields have been reported similar or higher with direct seeding than with transplanting when shorter-duration rice cultivars were used (Dingkuhn *et al.*, 1991a,b). Shorter duration of the crop also allows integration of more and different crops to enhance intensification/diversification of the production system.

9. A Dry Direct Drill-Seeded Rice Technology Package for the Major Rice-Based Systems in South Asia

Dry direct drill seeding has great potential in South Asia as an alternative to the conventional practice of puddled transplanting to overcome emerging resource constraints, especially labor, water, and energy shortages, and to address the increasing cost of cultivation. However, the performance of Dry-DSR has not yet reached its full potential in South Asia, primarily because of the unavailability of a complete Dry-DSR production technology package. Both rice genotype development and resource management are critical for achieving optimal production under Dry-DSR. Earlier, we discussed potential plant traits whose selection could lead to an efficient plant type for DSR. In this section, we review the large quantity of work on resource management that has been carried out during the past decades by the Rice-Wheat Consortium of the Indo-Gangetic Plains (RWC) (Gupta *et al.*, 2006; Ladha *et al.*, 2009; RWC-IRRI, 2009) and elsewhere (Bazaya *et al.*, 2009, Prasad, 2005; Sen and Sharma, 2002). At least two major publications are available that describe a technological package for Dry-DSR (Gopal *et al.*, 2010; Gupta *et al.*, 2006). Here, we provide the current status of work and salient recommendations for growing a successful crop of Dry-DSR.

The most important prerequisites for a successful crop of dry direct drill-seeded rice are (1) precise land leveling, (2) good CE, (3) precise water management, and (4) effective and efficient weed management. These are discussed in detail below.

9.1. Precise land leveling

Good land leveling is an entry point for DSR because it (1) facilitates uniform and good CE, (2) permits precise and uniform water control and good drainage, (3) reduces the amount of irrigation water needed, (4) increases cultivation area because of fewer bunds, (5), improves input use efficiency (water, nutrients, and agrochemicals), and (6) increases crop productivity (Jat *et al.*, 2006, 2009; Lantican *et al.*, 1999; Rickman, 2002). In the Philippines, Lantican *et al.* (1999) observed correlation between DSR yield and precision of land leveling. They estimated an average yield loss of 0.9 t ha^{-1} due to deficiency in land leveling, which results primarily from water stress in areas not leveled.

Studies conducted by the RWC reported a widespread problem of poor leveling in South Asia (Jat *et al.*, 2006). Fields leveled by traditional methods generally have large variability across the field with frequent dikes and ditches. The average field slope in the IGP varies from 1° to 3° in the northwest (India and Pakistan) and from 3° to 5° 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. In 2001, laser-assisted precision land leveling was introduced as an entry point for the success of alternative tillage and CE practices in the region. It allowed planters/drills to place seed at a uniform distance and depth, and enabled uniform distribution of irrigation water across the field, resulting in uniform crop stand. Leveling of 1.5–2 cm of standard deviation has been recommended for dry drill seeding after zero-tillage (Kawasaki, 1989; Kimura *et al.*, 1999). Laser land leveling is the single most popular technology in the IGP, where it has spread rapidly on about 1.0 million ha in India (M. L. Jat personal communication) and 0.16 million ha in Pakistan (Ladha *et al.*, 2009).

9.2. Crop establishment

Uniform crop emergence with optimum plant density is crucial for achieving good yields for any system, including direct drill-seeded rice. Good CE depends on many factors, including land preparation, planting date, seed rate and seed preparation, types of planting machinery used, and depth of seeding.

9.2.1. Land/seedbed preparation

The method of seedbed preparation differs for conservation (reduced or zero-till) and conventional-till systems. But, for both, the seedbed should be free of weeds and precisely leveled at the time of sowing. For conventional-till dry drill seeding (CT-dry-DSR), the soil should be well pulverized to maintain good soil moisture for drilling and good soil-to-seed contact. In sandy or silt loam, an excellent seedbed can be prepared with reduced or minimum tillage, thereby conserving soil, and reducing cost. In zero-till dry drill seeding (ZT-dry-DSR), it is important to first knock down the existing vegetation (annual and perennial weeds) with a burndown herbicide such as paraquat (0.5 kg ai ha^{-1}) or glyphosate (1.0 kg ai ha^{-1}).

9.2.2. Planting dates

Rice in South Asia is mainly grown during the monsoon season (wet season). In India and Nepal, it is commonly known as *kharif* and in Bangladesh as the *aman* season. To effectively use monsoon rain, the optimum time for planting wet-season rice is about 10–15 days prior to the onset of monsoon (based on forecast or historical weather data) (Gopal *et al.*, 2010; Gupta *et al.*, 2006). After the onset of rain when soil gets wet, movement of machinery becomes difficult, which makes seeding tedious. Moreover, if rain continues for a few days, seed rotting and seedling mortality can occur due to submergence, resulting in poor CE. Based on the historical trend of the onset of monsoon in different areas in the region, the optimum time for seeding rice is given in Table 15.

Table 15 Optimum sowing time in relation to onset of monsoon for dry direct-seeded rice in South Asia

Area	Onset of monsoon	Optimum time of seeding
Punjab, India	July 1–15	Mid-June to third week of June
Haryana, India	June 20–July 1	First fortnight of June
Western Uttar Pradesh, India	June 20–July 1	First fortnight of June
Eastern UP and Bihar, India	June 10–15	Last week of May to early June
West Bengal, India	June 1–15	Last week of May
Tarai, Nepal	June 15–July 7	End of May to mid-June

Source: Modified from Gopal *et al.* (2010).

9.2.3. Priming of seeds and seed treatment

Priming of seeds has been shown to have positive effects on the emergence, yield, and quality of dry direct-seeded rice (Farooq *et al.*, 2006a,b; Harris *et al.*, 2002). In dry drill seeding, good CE is constrained by subsurface soil drying associated with high temperature. Hence, priming of seeds (prehydration) offers the advantage of early and improved emergence, and early vigor. Priming is accomplished by soaking seeds in water for 10–12 h and then drying them in shade prior to seeding. This process facilitates a free flow of seed during seeding operations. However, seeds should be sown shortly after priming to avoid deterioration. Emergence of primed seeds will be affected if seeds encounter moisture stress initially. Therefore, seeding with primed seeds should be done only after pre-sowing irrigation.

Seed rot and seedling mortality are caused by various soil- and seed-borne fungi or other pathogens such as termites and nematodes (Krausz and Groth, 2008). Fungicide and/or insecticide seed treatments have been shown to improve the crop stand in many crops, including in dry drill seeding of rice (Krausz and Groth, 2008). Insecticides such as imidacloprid (Gaucho 70 WS) and thiamethoxam (Cruiser 5 FS) and fungicides such as carbendazim, streptocycline, metalaxyl, thiram, and mancozeb can be used for seed treatment (Gopal *et al.*, 2010; Gupta *et al.*, 2006; Tarun Sharma, personal communication). Both dry and primed seed can be treated. For primed seed, treatment with fungicide or insecticide should be done post-soaking. Damage by rice Thrips on emerging seedlings could also be controlled by using seed treatments.

9.2.4. Seed rate

The published literature shows a widespread use of seed rates of up to 200 kg ha^{-1} to grow a DSR crop (Guyer and Quadranti, 1985). High seed rates are used mostly in areas where seed is broadcast with an aim to suppress weeds or when water-seeded (Moody, 1977). However, it is not clearly known whether a high seed rate is primarily used to control weeds or is really a requirement to raise a good crop of DSR. Studies have reported an increase in yield only in weedy plots and not in weed-free or weeded plots with increases in seed rate. Therefore, higher seedling rates can be beneficial only in conditions with no or partial weed control (Castin and Moody, 1989; Guyer and Quadranti, 1985). Farmers also use high seed rate when conditions for germination are poor due to damage by birds, insects, rats, etc. or the germination percent of seed itself is low. The benefits of a higher panicle number associated with a higher seed rate are offset by a reduction in panicle length and grain weight per panicle (Bhattacharjee, 1978).

When using a drill for seeding, the seed rate can be decreased drastically without causing any adverse effect on yield if weeds are controlled effectively. Based on recent experience with on-farm farmer participatory trials 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). Very few on-station studies have been conducted evaluating the effects of seed rate to assess the performance of Dry-DSR. Sudhir-Yadav *et al.* (2007) evaluated seed rates of 30, 40, and 50 kg ha^{-1} for basmati rice in Punjab, India, and found that a seed rate of 30 kg ha^{-1} yielded the highest. Wu *et al.* (2008) in China found a seed rate of 20–25 kg ha^{-1} as optimum for DSR, including under zero-till conditions (ZT-dry-DSR). However, others found no difference in yield with a range of seed rates (Gravois and Helms, 1992; Johnson *et al.*, 2003; Jones and Snyder, 1987; Xie *et al.*, 2008).

High seed rates can result in large yield losses due to excessive vegetative growth before anthesis followed by a reduced rate of dry matter accumulation 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 (Baloch *et al.*, 2007; Huan *et al.*, 1999; Kabir *et al.*, 2008; Tuong *et al.*, 2000). Moreover, dense plant populations at high seed rates can create favorable conditions for diseases (e.g., sheath blight; Mithrasena and Adikari, 1986; Guzman Garcia and Nieto Illidge, 1992) and insects (e.g., brown planthoppers) and make plants more prone to lodging (Dofing and Knight, 1994; Islam *et al.*, 2008). A high seed rate also increases establishment costs.

Plant spacing has a major effect on crop yields. Huan *et al.* (1999) showed that, as the seed rate increases, tillering decreases and panicle density is more dependent on primary than on secondary or tertiary tillers. Since panicles from primary tillers are more productive than those from secondary and tertiary tillers, we should target an optimal spacing to have more panicles from primary tillers by minimizing interplant competition. Much research on plant spacing is done for optimizing transplanting (De Datta, 1981). If we follow this lead, then plant spacing in direct seeding should be similar to that in transplanting, if weed control is good. This means that a high seed rate is not needed in DSR to achieve high yields. More research is needed, however, to study the interaction of seed rate, variety, seed depth, spacing, and geometry.

9.2.5. Planting machinery (drills/planters)

For accurate and precise seeding, the crop should be drilled using a multi-crop planter with a precise seed-metering system (e.g., inclined plate, cupping system, or vertical plates) (Fig. 11B–D; Gopal *et al.*, 2010; Gupta *et al.*, 2006). With these precise seed-metering planters, rice can be established with a lower seed rate and more precise plant-to-plant spacing can be maintained. Normal fluted roller-type seed-cum-fertilizer drills are less suitable for drill seeding of rice as the seeds fall continuously. This makes it difficult to maintain the seed rate and plant-to-plant spacing as accurate and precise as that in inclined-/cupping-/vertical-plate seed-metering systems (Gopal *et al.*, 2010; Gupta *et al.*, 2006). It is difficult to drill rice at a low seed rate of 20–25

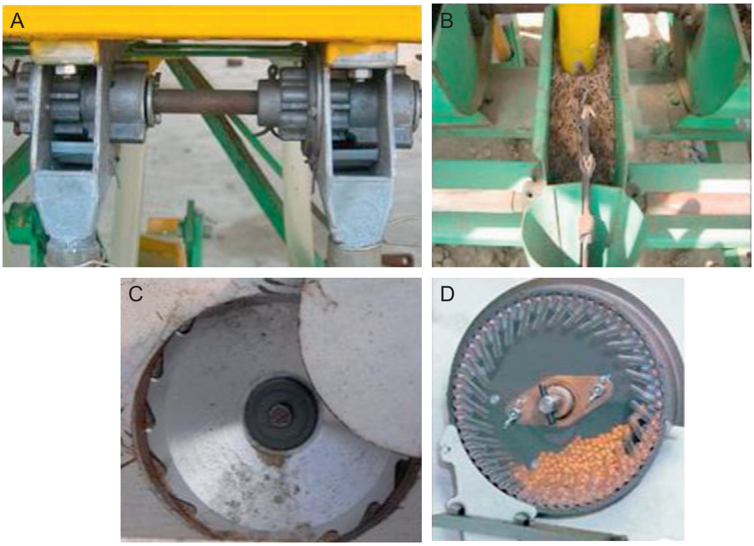

Figure 11 Multicrop planter's seed-metering systems, (A) fluted roller, (B) cup type, (C) inclined plate, and (D) vertical plate. Source: Gupta *et al.* (2006) and Gopal *et al.* (2010).

kg ha^{-1} with a fluted roller seed drill because it breaks the seeds. If farmers do not have inclined-plate planters, they can seed at a lower rate with a normal drill by mixing 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). *Sesbania* (a leguminous green manure) seeds can also be mixed to achieve the same purpose. *Sesbania* is then killed with 2,4-D about 30 days after seeding (Singh *et al.*, 2007). The PTOS is most commonly used for seeding rice in Nepal and Bangladesh. The PTOS has a seeding device attached to the power tiller (Chinese hand tractor). It tills the soil shallow (4–5 cm), sows seed in rows, and covers it with soil at the same time in a single pass.

Specialized machines are required for ZT-dry-DSR with loose crop residue. Recently, different machines have been evaluated and refined to seed under loose residue, especially after combine harvest in South Asia (Gopal *et al.*, 2010; Sharma *et al.*, 2008; Sidhu *et al.*, 2008; Singh, 2008). Some of the machines that can be used for seeding rice with surface residues are briefly discussed here:

9.2.5.1. Turbo seeder With this machine, rice can be drilled into a loose residue mulch load of up to 8–10 t ha^{-1} (Gopal *et al.*, 2010; M. K. Gathala, personal communication). It shreds the residues in the narrow strip in front of the tine openers and places seeds and fertilizer using an inverted-T-type opener. The seed-metering system on currently manufactured machines comprises fluted rollers, as this machine was originally designed for sowing wheat into rice residues. Minor redesign is in progress to provide a better seeding mechanism (inclined plate) for rice.

9.2.5.2. PCR planter This is an advanced version of the turbo seeder/planter. It has a multicrop precise seed-metering system (vertical plates) with adjustable row arrangements. It is capable of seeding into a residue load of up to 8–10 t ha^{-1} (Gopal *et al.*, 2010).

9.2.5.3. Double-disc coulters In this machine, double-disc coulters are fitted in place of tines to place seed and fertilizer into the loose residues. This machine can drill seeds into a loose residue load of up to 3–4 t ha^{-1}. A limitation with this machine is that, being lightweight (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; Sharma *et al.*, 2008).

9.2.5.4. Rotary-disc drill It is based on a rotary-till mechanism. It is mounted on a three-point linkage system and is powered through the power take-off shaft of the tractor. The rotor is a horizontal transverse shaft having six to nine flanges fitted with a straight disc for a cutting effect while rotating at 220 rpm (Singh *et al.*, 2008). The rotating discs cut the residue and make a narrow slit into the soil to facilitate placement of seed and fertilizer. This machine can be used under loose residue, anchored residue, and residue-free conditions. It can handle a residue load of 7–8 t ha^{-1}. This machine's limitation is the blunting of front-powered discs, which, however, can be overcome by using discs of greater strength (Sharma *et al.*, 2008).

9.2.6. Depth of seeding and moisture

Seeding depth is critical for all rice varieties but more so for semi-dwarf plant types because of their shorter mesocotyl length compared with conventional tall varieties (Blanche *et al.*, 2009). Therefore, rice should not be drilled deeper than 2.5 cm to maximize uniform CE. It is important to have sufficient moisture during the germination period. As sowing is done during peak summer when the open-pan evaporation rate is as high as 8–12 mm day^{-1}, the soil surface can dry very quickly and the seed zone can experience moisture stress (Gopal *et al.* 2010; Tabbal *et al.*, 2002).

Rice can either be drilled in dry soil followed by a light irrigation or drilled in moist soil after preirrigation to ensure good emergence and uniform establishment. In the latter situation, planking after seeding will conserve soil moisture and improve soil-to-seed contact.

9.3. Precise water management

Precise water management, particularly during CE phase (first 7–15 days after sowing), is crucial in dry drill-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. Therefore, early weed control with an effective preemergence herbicide is very important to check weed emergence and growth.

As already discussed, precise leveling is crucial for the uniform spread of water as well as easy drainage which is needed during the CE phase of Dry-DSR. When water control and/or drainage are poor, the crop is likely to fail due to submergence in the early stage. Bund management also plays an important role in maintaining uniform water depth and limiting water losses via seepage and leakage (Lantican *et al*., 1999; Tuong *et al*., 1994). It is important that the bunds be prepared as soon as possible after sowing, which includes compacting and plastering of any holes or cracks.

Information on irrigation and water management in Dry-DSR is scarce (Humphreys *et al*., 2010). Gupta *et al*. (2006) and Gopal *et al*. (2010) recommended avoiding water stress and keeping the soil wet at the following stages: tillering, panicle initiation, and grain filling. Bouman *et al*. (2007) suggested keeping the field flooded 1 week before and after peak flowering to avoid water stress around flowering, the most sensitive stage of rice to water stress. After CE, the following four broad water management options are available: (1) continuous flooding; (2) frequent irrigation, that is, DSR with safe alternate wetting and drying (AWD), which involves flooding the field with shallow depth (5 cm) and reirrigating a few days after water disappearance; (3) infrequent irrigation where scarcity of irrigation water limits rice yields; and (4) no irrigation under rainfed conditions (Humphreys *et al*., 2010). Given the aim of achieving high yields of Dry-DSR with less water, option 2 is preferred but this is subject to the availability of irrigation water. Like CT-TPR, Dry-DSR can also be irrigated using safe AWD to economize in water use. However, our knowledge in terms of optimal soil water status to implement safe AWD in Dry-DSR is still limiting. Nevertheless, farmers and researchers provide many anecdotal reports indicating that a safe AWD irrigation interval in Dry-DSR is longer than that in CT-TPR because of less soil cracking in the former than in the latter (Humphreys *et al*., 2010). 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 (Bhushan *et al*., 2007; Gathala *et al*., 2011). This study recorded an average savings of 9% irrigation water when irrigation took place on the appearance of soil hairline cracks (this coincided with −25 to −35 kPa at 15-cm depth). Another study conducted by Sudhir-Yadav *et al.* (2011a,b) in Punjab, India on clay loam soil observed −20 kPa soil tension at 20 cm depth as safe for AWD irrigation scheduling. They observed 33–53% irrigation water saving in Dry-DSR with AWD compared with CT-TPR without compromising grain yield. Further research is needed to determine the optimum threshold for irrigation at different growth stages and for a wider range of rainfall and evaporative demand conditions and varietal types. Moreover, Dry-DSR with residue mulch would also require appropriate irrigation scheduling and water management as residue mulch would influence evaporation, infiltration, and transpiration very differently than conventional practice.

A large area of the rice–wheat cropping system of South Asia is irrigated primarily from groundwater. Any attempt to reduce deep drainage losses in these areas would neither save water nor reduce groundwater decline (Humphreys *et al.*, 2010) because often that water is reused/pumped. However, reductions in deep percolation losses can save energy (energy needed to pump) and reduce groundwater pollution. To have a significant impact on true water savings, we need technologies that can reduce ET and increase water productivity of evapotranspired water (WP_{ET}) (Humphreys *et al.*, 2010). For example, residue mulch in Dry-DSR may significantly reduce *E* and ET, especially prior to the start of monsoon when evaporation is very high and plants are very small (Jalota and Arora, 2002). The development of new cultivars of short to medium duration adapted to water limitations is another approach to reducing irrigation water use (Humphreys *et al.*, 2010).

Recently, interest has been increasing in using pressurized irrigation method to grow rice in areas where water is becoming scarce (Spanu *et al.*, 1996). Limited studies in the region have shown that sprinkler systems have potential to improve on-farm irrigation efficiency up to 80% in other crops under the prevailing conditions in the Indian subcontinent (Sharma, 1984). Sprinkler systems can be used in rice to apply a desired depth of water during pre- and post-sowing irrigations (Kahlown *et al.*, 2007). In Pakistan, Kahlown *et al.* (2007) found that sprinkler irrigation increased the grain yield of CT-TPR by 18% and reduced water application by 35% compared with the traditional irrigation system. Similarly, Kato *et al.* (2009) in Japan found that Dry-DSR when irrigated with a sprinkler system (30–40 mm) whenever soil water potential fell below −60 kPa at 20-cm depth produced equal or higher yield than transplanted or dry direct-seeded rice under a flooded system, with total water savings ranging from 21% to 74%. Although some of these studies show potential, much needs to be done to understand the feasibility and economics of pressurized irrigation methods in farmers' fields when land holdings are small. This area seems to have huge untapped potential which should be explored in close collaboration with various partners, especially in the private sector.

9.4. Effective and efficient weed management

IWM is desirable for effective and sustainable weed control in Dry-DSR (Rao and Nagamani, 2007; Rao *et al.*, 2007). Effective IWM integrates many "little hammers" instead of a single "large hammer" (e.g., herbicides) to control a wide range of weeds at many points in their life cycle (Liebman and Gallandt, 1997). Tools available for IWM can be categorized broadly into (a) cultural, (b) chemical, (c) mechanical, and (d) biological controls. Here, we review the published studies that have shown effective management strategies that can be integrated to manage weeds in Dry-DSR. IWM can also be enhanced through an understanding of the biology and ecology of specific problematic weeds to help identify weak points in weed life histories that can be efficiently targeted for management.

9.4.1. Cultural practices

9.4.1.1. The stale seedbed technique In this technique, after seedbed preparation, the field is irrigated and left unsown to allow weeds to germinate. Following emergence, weeds are killed either by a nonselective herbicide (usually paraquat or glyphosate) or by carrying out tillage prior to the sowing of rice. This technique not only reduces weed emergence but also reduces the number of weed seeds in the soil seedbank (also referred to as the soil weed seedbank) (Rao *et al.*, 2007). Singh *et al.* (2009b) reported 53% lower weed density in Dry-DSR after a stale seedbed than without this practice. The success of stale seedbeds depends on several factors: (a) method of seedbed preparation, (b) method of killing emerged weeds, (c) weed species, (d) duration of the stale seedbed (Ferrero, 2003), and (e) environmental conditions (e.g., temperature) during the stale seedbed period. Weed species, especially *C. iria*, *C. difformis*, *F. miliacea*, *L. chinensis*, and *Eclipta prostrata* (L.), can be relatively more susceptible to the stale seedbed technique combined with zero-till because of their low seed dormancy and their inability to emerge from a depth greater than 1 cm (Chauhan and Johnson, 2008a,b; Chauhan and Johnson, 2009, 2010). Renu *et al.* (2000) found that a stale seedbed with herbicide (paraquat) was more effective in weed suppression than with the mechanical method in Dry-DSR because herbicides kill weeds without bringing new seeds to the germination zone. Ideally, the duration of the stale seedbed should be long enough to allow the maximum emergence of weeds to the two- to three- leaf stage. However, in practice, the duration of the stale seedbed may be determined by the optimal planting timing for rice.

9.4.1.2. Land preparation—tillage and leveling Land preparation including tillage and precise land leveling before crop planting plays an important role in controlling weeds in dry drill-seeded rice. Tillage determines the vertical distribution of weed seeds in the soil profile, which in turn affects seedling establishment depending on factors such as seed predation, seed dormancy, seed longevity, and the potential of seedlings to emerge from a given depth (Chauhan *et al.*, 2006). Zero tillage can reduce weed problems and make management easier if weeds are managed effectively in the initial 2–3 years. Zero tillage may also reduce weed emergence of some species as the seeds at the soil surface are more prone to predation (Jacob Spafford *et al.*, 2006) and desiccation (Mohler and Galford, 1997). In addition, the physical environment created by surface residue in a ZT system provides a habitat for weed seed predators and also offers conditions more conducive to microbial decay of weed seeds because of more microbial activity (Gallandt, 2006; Gallandt *et al.*, 1999). Therefore, for annual weeds (reproduced primarily by seeds), reduced tillage may result in reduced weed seed survival and emergence in the long run with the assumption that weed seed production is not increased in reduced-tillage systems. However, for perennial weeds [reproduce vegetatively, or through underground tubers (e.g., sedges)], a lack of tillage may exacerbate weed problems if weeds are not controlled effectively by a nonselective herbicide (glyphosate) prior to crop planting. In situations where weed control is suboptimal and the weed seed load is relatively high, conventional tillage may be a more suitable option as tillage can bury weed seeds below germination zones and can reduce weed problems.

Precise land leveling helps improve weed control by enabling precise water control and improving herbicide efficiency. This has been shown to be effective in reducing the weed population up to 40%, the labor requirement for weeding by 75% (16 person-days ha^{-1}), and weeding cost by 40% (Rickman, 2002). By and large, land leveling has been overlooked as an option for managing weeds. More work in this area would clarify the exact role of land leveling in weed dynamics and composition.

9.4.1.3. Sesbania *coculture* *Sesbania* is a legume used as a green manure in rice cultivation either as pre-rice or an inter- or mixed crop with rice (Singh *et al.*, 2009b). It is sown at 25 kg ha^{-1} together with rice. After 25–30 days of growth, when *Sesbania* is about 30–40 cm tall, it is killed with 2,4-D ester at 0.50 kg ha^{-1}. This coculture technology can reduce the weed population by nearly half without any adverse effect on rice yield. Singh *et al.* (2007) reported that *Sesbania* coculture 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. This may largely be due to the rapid growth of *Sesbania* and, to some extent, mulch effects of its biomass.

The effectiveness of this technique is further enhanced by the application of pendimethalin, a preemergence herbicide. Pendimethalin is effective in controlling grass weed species, which otherwise become difficult to control after knockdown of *Sesbania* because of their large size. *Sesbania* followed by 2,4-D was more effective in suppressing broadleaves and sedges and less effective on grasses. Therefore, it is recommended to use pendimethalin as a preemergence to overcome the problem of grass control in this technique.

In addition to weed suppression, other benefits of *Sesbania* coculture are atmospheric nitrogen fixation and facilitation of crop emergence in areas where soil crust formation is a problem (Gopal *et al.*, 2010; Singh *et al.*, 2009b). Despite these benefits, *Sesbania* coculture may pose risks of competition with rice if 2,4-D application is ineffective or 2,4-D application is delayed due to continuous rain and could also increase the cost of production. Moreover, *Sesbania* coculture may limit the use of herbicides as some of these herbicides may kill *Sesbania* also.

9.4.1.4. Residue mulching Retaining crop residue on the soil surface as mulch can suppress weeds by reducing the recruitment of seedlings and early growth. Residue mulch can suppress weeds by (a) providing a physical barrier to emerging weeds (Mohler, 1996; Mohler and Callaway, 1991; Mohler and Teasdale, 1993) and (b) releasing allelochemicals in the soil with decomposition (Chou, 1999; Weston, 1996). Limited research has been done in rice-growing regions to determine the potential of mulching for weed suppression in DSR. A study conducted in India found that wheat residue mulch of 4 t ha^{-1} reduced the emergence of grass weeds by 44–47% and of broadleaf weeds by 56–72% in dry drill-seeded rice (Singh *et al.*, 2007). This reduction in weed emergence resulted in 17–22% higher grain yield in mulched plots compared with unmulched plots. Information on the amount of residue required to suppress weeds without hindering CE is lacking. In a pot experiment in the Philippines, Chauhan and Johnson (2010) reported that rice residues ranging from 2 to 6 t ha^{-1} inhibited and delayed the emergence and biomass of many rice weed species, including *E. colona*, *E. crus-galli*, *Digitaria ciliaris*, *Dianella longifolia*, and *Eleusine indica*. In actual field conditions, higher amounts of crop residue may be required to be effective in weed suppression. In South Asia, there is a competition for crop residue with animal feed (RWC-CIMMYT, 2003). The retention of crop residues has also been advocated in the intensive rice–wheat system in the region because of increasing concern about depleting soil organic matter and environmental pollution with the burning of crop residues (Gupta *et al.*, 2006).

Because of puddling and the flooding nature of conventional rice culture, not much attention has been paid to the use of residue mulch, including in DSR. However, zero tillage followed by direct seeding provides an opportunity to use residue as mulch. In combine-harvested fields, crop residues should be spread uniformly before planting to ensure optimal CE (Singh *et al.*, 2009b). As discussed earlier, multicrop new-generation ZT drills/planters, Turbo Happy Seeders, and rotary-disc drills allow seeding in loose and standing residues.

9.4.2. Chemical measures

Chemical control measures are generally more targeted at the early stage of weed emergence and growth when weed control is easier. Once weeds become big, they are difficult to control (Bastiaans *et al.*, 2008). In dry direct drill-seeded rice, the "critical period" of weed competition has been reported to be 15–45 days after seeding (Rao and Nagamani, 2007; Singh *et al.*, 1999; Yaduraju and Mishra, 2004). If weeds can be suppressed effectively during this period, minimal yield losses occur.

It is crucial to select the right herbicide depending upon the weed flora present in a given field. In addition, the correct rate, timing, and application techniques should be used. A variety of herbicides have been screened and found effective for preplant/burndown, preemergence, and postemergence weed control in dry direct drill-seeded rice systems, including under zero-tillage conditions. Table 16 provides an inventory of various available herbicides and their target weeds.

9.4.2.1. Preplant/burndown herbicides Preplant/burndown herbicides are used to control existing annual and perennial weeds prior to rice sowing, especially under the ZT system. Glyphosate (1 kg ai ha^{-1} or 0.5–1.0% by volume) and paraquat (0.5 kg ai ha^{-1} or 0.5% by volume) are recommended for burndown application (Gupta *et al.*, 2006). Glyphosate is a systemic nonselective herbicide, and it controls most annual and perennial weeds. To be effective, it should be applied when weeds are growing actively so that the herbicide is absorbed and translocated into the entire plant system. For the same reason, grazing of fields should be avoided. In a situation where the weeds are under stress, a light irrigation before spraying glyphosate is recommended. Paraquat is a nonselective contact herbicide, and it should be used in fields infested with annual weeds. This herbicide should be avoided in situations where fields are infested with perennial weeds. Clear water should be used for making a spray solution as these herbicides bind with suspended soil particles and metal surfaces (iron buckets), thereby reducing their efficiency (Gopal *et al.*, 2010). Nonreactive surfaces such as plastic containers should be used for preparing solutions. Moreover, the application of preplant herbicides is more effective when the weed foliage is fully exposed and is not submerged. If necessary, fields should be drained before application.

Table 16 Major herbicides used in direct-seeded rice and their target weed species

	Weed species	Preemergence		Postemergence									
		Pendimethalin	Oxadiargyl	Bispyribac	Penoxsulam	Fenoxaprop	Cyhalofop	Propanil	Azimsulfuron	Ethoxysulfuron	Triclopyr	2,4-D	Chlorimuron + metsulfuron
A.	Grass												
1	*Echinochloa crus-galli*	+	+	+	+	+	+	+	±	−	−	−	−
2	*E. colona*	+	+	+	+	+	+	+	±	−	−	−	−
3	*Leptochloa chinensis*	+	+	−	−	+	+	+	−	−	−	−	−
4	*Ergrostis japonica*	+	NA	−	−	+	+	+	NA	−	−	−	−
5	*Dactyloctenium aegyptium*	+	+	−	−	+	+	+	±	−	−	−	−
6	*Eleusine indica*	+	NA	−	±	+	NA	+	±	−	−	−	−
7	*Brachiaria reptans*	+	NA	−	−	+	+	+	NA	−	−	−	−
B.	Broadleaf												
8	*Eclipta alba*	+	+	+	+	−	−	+	+	+	+	+	+
9	*Caesulia axillaris*	NA	NA	NA	+	−	−	NA	+	NA	+	+	
10	*Sphenoclea zeylanica*	+	NA	+	+	−	−	±	+	NA	+	+	+
11	*Alternanthera sessile*	+	NA	NA	±	−	−	+		NA	+	+	
12	*Ammannia baccifera*	+	NA	NA	±	−	−	±	+	+	+	+	+
13	*Ludwigia quadrifolia*	+	+	+	±	−	−	±	+	NA		+	+
14	*Commelina* species	−	NA	+	+	−	−	NA	NA	NA	+	+	+
15	*Marsilea quadrifolia*	+	+	+	NA	−	−	NA	NA	+	NA	NA	+
16	*Monochoria*	NA	NA	+	+	−	−	±	NA	+		+	+
17	*Lindernia crustacea*	NA	NA	NA	+	−	−	+	+	NA	+	+	
18	*Trianthema portulacastrum*	+	NA	+	+	−	−	−	+	+	±	−	+
C.	Sedge												
19	*Cyperus iria*	+	+	+	+	−	−	+	+	+	+	±	+
20	*C. difformis*	+	+	+	+	−	−	+	+	+	±	±	+
21	*C. rotundus*	−	NA	±	±	−	−	−	+	+	NA	NA	±
22	*Fimbristylis miliacea*	+	NA	+	+	−	−	+	+	+	+	+	+

+, controlled; −, not controlled; ±, suppressed; NA, information not available.

9.4.2.2. Preemergence herbicides Pendimethalin (1.0 kg ai ha^{-1}), oxadiargyl (0.09 kg ai ha^{-1}), and pyrazosulfuron (0.02 kg ha^{-1}) have been reported to be effective preemergence herbicides to control weeds in dry direct-seeded rice (Gupta *et al.*, 2006; Rao and Nagamani, 2007, Singh *et al.*, 2009b; Gopal *et al.*, 2010). Good soil moisture is essential for the activation of preemergence herbicides. Pendimethalin should be applied after rice seed has imbibed germination water, that is, 2–3 days after sowing to avoid crop injury.

9.4.2.3. Postemergence herbicides Herbicides that have been found to be effective for postemergence weed control in the Dry-DSR system with their dose, time of application, mode of action, and strengths and weaknesses have been summarized in Table 17. Continuous use of a single herbicide on a long-term basis should be avoided; rather, it should be rotated with another herbicide with a different mode of action to avoid/delay resistance development. Tank mixtures of herbicides can be used when two or more herbicides are compatible to broaden the spectrum of weed control in such a way that each herbicide controls the weeds missed by the other one. The herbicide mixtures listed in Table 17 have been found to be effective in better controlling a combination of weeds, including grasses, broadleaves, and sedges.

9.4.3. Manual and mechanical methods of weed control

Relying only on manual weeding is not economical in most situations. One or two spot hand weedings may sometimes be necessary to remove weeds that have not been controlled by other weed control methods. For mechanical weeding, rotary weeders and cono weeders have been found effective in controlling weeds in DSR. More details on manual and mechanical methods of weed control can be obtained from reviews by Rao *et al.* (2007) and Singh *et al.* (2009b).

A well-leveled zero-tilled land coupled with a stale seedbed and residue mulch can be an effective method for suppressing weeds in Dry-DSR. Other cultural practices that help reduce weed pressure in Dry-DSR include the use of clean and certified seeds, keeping bunds and canals clean, good CE, varieties with greater weed-suppressive ability, and precise and proper water management (Singh *et al.*, 2009b).

In summary, the components of integrated strategies for weed control in DSR are (1) the stale seedbed technique, (2) the use of clean and certified seeds, (3) new herbicide chemistries appropriate to DSR conditions, (4) high-yielding rice varieties with greater early vigor and weed-competitive ability, (5) precise water management, (6) the use of mechanical tools and manual hand weeding, (7) the use of crop residues for weed suppression, and (8) the use of tillage practice (e.g., zero tillage), which provides habitat for seed predation and seed decay.

Table 17 Major pre- and postemergence herbicides used in direct-seeded rice in South Asia with application dose, timing, and their strengths and weaknesses

Herbicide	Dose (g ai ha^{-1})	Application time (DAS)[a]	Mode of action	Strengths	Weaknesses
Pendimethalin	1000	1–3	Microtubule assembly inhibitor	Good control of most grasses, some broadleaves and annual sedges. Has residual control	Sufficient moisture is needed for its activity
Oxadiargyl	90	1–3	Protoporphyrinogen oxidase inhibitor	Broad-spectrum weed control of grasses, broadleaves and annual sedges. Has residual control	Sufficient moisture is needed for its activity
Pyrazosulfuron	20	1–3 or 15–20 DAS	ALS inhibitor[b]	Broad-spectrum weed control of grasses, broadleaves and sedges including *C. rotundus*. Has residual control	Poor on grasses, including *L. Chinensis* and *Dactyloctenium aegyptium*

(*Continued*)

Table 17 (*Continued*)

Herbicide	Dose (g ai ha^{-1})	Application time (DAS)[a]	Mode of action	Strengths	Weaknesses
Bispyribac-sodium	25	15–25	ALS inhibitor	Broad-spectrum weed control of grasses, broadleaves and annual sedges. Excellent control of *Echinochloa* species	Poor on grasses other than *Echinochloa* species, including *L. chinensis*, *Dactyloctenium aegyptium*, *Eleusine indica*, *Ergrostis species*. No residual control
Penoxsulam	22.5	15–20	ALS inhibitor	Broad-spectrum weed control of grasses, broadleaves and annual sedges	Poor control of grasses other than *Echinochloa,* including *L. chinensis, D. aegyptium, Eleusine indica, Ergrostis species*
Fenoxaprop-ethyl	60	25	ACCase inhibitor[c]	Excellent control of annual grassy weeds	Does not control broadleaves and sedges. Not safe on rice if applied at early stage (before 25 DAS).

Fenoxaprop-ethyl + safner	60–90	15–20	ACCase inhibitor	Excellent control of annual grassy weeds, safe on rice at early stage	Does not control broadleaves and sedges
Cyhalofop-butyl	120	15–20	ACCase inhibitor	Excellent control of annual grassy weeds	Does not control broadleaves and sedges
Propanil	4000	15–25	Photosynthesis at photosystem-II inhibitor	Broad-spectrum weed control, can be tank-mixed with many herbicides	No residual control. Need sequential application for effective control or need some residual herbicide with it as tank mix
Azimsulfuron	17.5–35	15–20	ALS inhibitor	Broad-spectrum control of grasses, broadleaves and sedges. Excellent control of sedges, including *Cyperus rotundus*	Poor on *Echinochloa* species
Ethoxysulfuron	18	15–20	ALS inhibitor	Effective on broadleaves and annual sedges	Does not control grasses and poor on perennial sedges such as *C. rotundus*

(*Continued*)

Table 17 (*Continued*)

Herbicide	Dose (g ai ha^{-1})	Application time (DAS)[a]	Mode of action	Strengths	Weaknesses
Triclopyr	500	15–20	Synthetic auxins	Effective on broadleaf weeds	Does not control grasses
2,4-D ethyl ester	500	15–25	Synthetic auxins	Effective on broadleaves and annual sedges. Very economical	Has no residual control
Carfentrazone	20	15–20		Effective on broadleaf weeds	Does not control grasses. Has no residual control
Chlorimuron + metsulfuron	4 (2 + 2)	15–25	ALS inhibitor	Effective on broadleaves and annual sedges	No control of grassy weeds and poor on *C. rotundus*
Bispyribac + azimsulfuron	25 + 17.5	15–25	ALS inhibitor	Broad-spectrum weed control of grasses, broadleaves and sedges, including *C. rotundus*	Poor on grasses other than *Echinochloa* species

Fenoxaprop + ethoxysulfuron	56 + 18	15–25	ACCase and ALS	Broad-spectrum weed control of grasses, broadleaves and sedge. Excellent control of all major grasses, including *L. chinensis* and *D. aegyptium*	Poor on perennial sedges such as *C. rotundus*
Propanil + pendimethalin	4000 + 1000	10–12 DAS	Photosynthesis and microtubule assembly inhibitor	Broad-spectrum weed control with residual effects	Poor on sedges such as *C. rotundus*
Propanil + triclopyr	3000 + 500	15–25	Photosynthesis and synthetic auxins	Broad-spectrum weed control of grasses, broadleaves and sedges	Poor control on perennial sedges such as *C. rotundus*. No residual control

[a] Days after sowing.
[b] Acetolactate synthesis inhibitor.
[c] Acetyl-coenzyme A carboxylase synthesis inhibitor.

9.5. Fertilizer management

Much work on fertilizer management in rice has been carried out for CT-TPR but limited work has been conducted in Dry-DSR, including ZT-dry-DSR. In Dry-drill-DSR, because of more aerobic conditions and alternate wetting/drying cycles, the availability of several nutrients including N and micronutrients such as Zn and Fe, is likely to be a constraint (Ponnamperuma, 1972). In addition, loss of N due to nitrification/denitrification, volatilization, and leaching is likely to be higher in Dry-DSR than in CT-TPR (Musa 1969; Davidson, 1991; Singh and Singh, 1988; Patrick and Wyatt, 1964).

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). This is 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. Early studies conducted in Korea indicated that 40–50% more N fertilizer should be applied in Dry-DSR than in CT-TPR (Park *et al.*, 1990; Yun *et al.*, 1993), although higher N application also leads to disease susceptibility and crop lodging. The general recommendation is to apply a full dose of P and K and one-third N as basal at the time of sowing using a seed-cum-fertilizer drill/planter. This allows placement of the fertilizer just below the seeds and hence improves fertilizer efficiency. Split applications of N are necessary to maximize grain yield and to reduce N losses and increase N uptake. Split applications ensure a supply of N to match crop demand at the critical growth stages. The remaining two-third dose of N should be applied as topdressing in equal parts at active tillering and panicle initiation stage. In addition, N can be managed using a leaf color chart (LCC) (Shukla *et al.*, 2004; Alam *et al.*, 2005). 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 color. In the real-time option, farmers monitor the color of rice leaves at regular intervals of 7–10 days from early tillering (20 DAS) and N is applied whenever the color 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 (Shukla *et al.*, 2004; Gupta *et al.*, 2006; Gopal *et al.*, 2010). Since more N is applied in Dry-DSR and losses are higher than in CT-TPR, more efficient N management for Dry-DSR is needed.

Slow-release (SRF) or controlled-release N fertilizers (CRFs) offer the advantage of a "one-shot dose" of N and the option to reduce N losses because of their delayed release pattern, which may better match crop demand (Shoji *et al.*, 2001). One-shot application will also reduce labor cost. Fashola *et al.* (2002) reported that CRF improves N use efficiency and yield compared with untreated urea. Because of these benefits, CRF with polymer-coated urea is used by Japanese farmers in ZT-dry-DSR (Saigusa, 2005; Ando *et al.*, 2000). Despite these benefits, farmers' use of CRF is limited mainly because of the high costs associated with it. The cost of CRF may be four to eight times higher than that of conventional fertilizers (Shaviv and Mikkelsen, 1993). In addition, published results on the performance of SRFs/CRFs compared with conventional fertilizers are not consistent. Christianson and Schultz (1991), Stangel *et al.* (1991), Stutterheim *et al.* (1994), and Fashola *et al.* (2002) have demonstrated higher N use efficiency through the use of CRFs. Saigusa (2005) reported higher N recovery of co-situs (placement of both fertilizer and seeds or roots at the same site) application of CRF with polyolefin-coated ureas of 100-day type (POCU-100) than conventional ammonium sulfate fertilizer applied as basal and topdressed in zero-till direct-seeded rice in Japan. In contrast, Wilson *et al.* (1990), Wells and Norman (1992), and Golden *et al.* (2009) reported inferior performance of SRF or CRF compared with conventional urea topdressed immediately before permanent flood establishment.

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. Deficiency of Zn and Fe is more common in aerobic/non-flooded rice systems than in flooded rice systems (Sharma *et al.*, 2002; Singh *et al.*, 2002a; Hongbin *et al.*, 2006; Choudhury *et al.*, 2007; Pal *et al.*, 2008; Yadvinder-Singh *et al.*, 2008). Therefore, micronutrient management is critical in Dry-DSR. To avoid zinc deficiency, 25–50 kg ha^{-1} zinc sulfate is recommended (Anonymous, 2008, 2010). Basal application of zinc to the soil is found to be the best. However, if a basal application is missed, the deficiency can be corrected by topdressing up to 45 days (Anonymous, 2010). Zinc can be supplied by foliar application (0.5% zinc sulfate) two to three times at intervals of 7–15 days just after the appearance of deficiency symptoms. For iron, it has been observed that foliar application is superior to soil application (Datta *et al.*, 2003; Anonymous, 2010). 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 $FeSO_4{\cdot}7H_2O$ solution) has been found to be effective (Pal *et al.*, 2008).

10. Conclusions and Future Outlook

Today, conventional puddled transplanting is the most common practice of rice production in Asia. Because of the water-, labor-, and energy-intensive nature of this system, and rising interest in CA, dry-seeded rice (Dry-DSR) with zero or reduced tillage (ZT–RT) has emerged as a viable alternative. Projections and trends seem to suggest that Dry-DSR will likely be a major rice culture in many countries in the future. We have attempted to address several questions pertaining to DSR and discuss an integrated package of technologies specifically for ZT/RT-dry-DSR to address the fast-emerging water and labor crisis.

10.1. What are the different types of direct seeding and their niches?

Crop establishment, though using direct sowing, can vary from broadcasting manually or mechanically (aeroplane or power sprayer) to line sowing using either a drill or a drum seeder, or manually by the dibble method in puddled or unpuddled soil. In areas where labor scarcity has been serious but water is relatively more readily available, farmers shifted to Wet-DSR without making a change in tillage. However, in areas where both labor and water are emerging as major constraints, farmers are interested in Dry-DSR with zero or reduced tillage.

10.2. What are the major drivers of the shift from puddled transplanting to direct seeding?

The rising scarcity of water and labor are the major drivers for this shift. Puddled transplanting is the main user of freshwater, and it requires large amounts of labor. However, water and labor for agriculture are becoming increasingly scarce resources in many rice production areas. The share of water in agriculture is declining because of its increased demand in other nonagriculture sectors. Groundwater is being depleted at an alarming rate, especially in South Asia and North China, mainly because of its heavy use for rice production. Similarly, labor availability for agriculture is declining because of increased demand in nonagriculture sectors associated with rapid economic growth in many Asian countries. Moreover, in the current socioeconomic environment, most people, especially young workers, are unwilling to undertake tedious farm operations such as transplanting. In addition, high labor demand during the critical operation of transplanting leads to shortages and increasing labor costs. These factors provide incentives for farmers to shift to some form of direct seeding, which requires less water and labor. Other drivers include (1) economic incentives for crop intensification (from a single rice crop to double cropping in Vietnam and the Philippines) brought by DSR, (2) the adverse effect of puddling on physical properties of the soil and on the succeeding non-rice upland crop in rotation together with rising interest in CA, and (3) recent developments in production techniques along with the availability of new herbicides for weed control and short-duration varieties. Primarily because of labor shortages, direct seeding (mostly wet seeding) is widely adopted in Malaysia and Sri Lanka and is spreading rapidly in Vietnam, Thailand, and the Philippines.

10.3. What lessons have we learned from those countries where direct seeding is widely adopted?

In the United States, Malaysia, and Sri Lanka, more than 90% of the rice has been direct seeded for the past few decades. These case studies provide a few important lessons for the countries that are moving toward DSR. It is clear that precise land leveling, suitable cultivars, good CE, precise water management, and effective and efficient weed and nutrient management are keys to the success of DSR. The establishment of a strong herbicide industry resulting in the availability of affordable and appropriate herbicides has also played an important role in these countries. Experiences have also shown that a shift to DSR resulted in (1) weed flora changes toward more difficult-to-control and competitive grasses and sedges, (2) the development of resistance in weeds against commonly used herbicides, and (3) the appearance of weedy rice. Therefore, anticipatory research and development strategies need to be developed for areas where direct seeding is likely to be adopted. This is important for direct seeding to be sustainable on a long-term basis.

10.4. Can direct seeding be as productive as conventional puddled transplanted rice?

Available published data in the literature show variable responses of crop productivity under DSR. Wet-DSR with line sowing (CT-wet-DSR) tends to be as good as or superior to CT-TPR. Dry-DSR has been more inconsistent, with a yield penalty ranging from 7.5% to 28.5% in India and Pakistan, whereas in other countries, it was similar to CT-TPR. However, the gradual improvement in productivity observed in Wet-DSR is likely to also occur for the more recently introduced Dry-DSR systems as optimal complementary management practices are developed.

10.5. Does direct seeding save on the use of labor or water?

Published data from 44 studies show clear evidence of savings of 12–35% of irrigation water under DSR systems. Irrigation water savings ranked in the following order: Bed-dry-DSR > ZT-dry-DSR > CT-dry-DSR > CT-wet-DSR > CT-TPR. The irrigation water productivity of DSR methods was either similar (ZT-dry-DSR and Bed-dry-DSR) or higher (CT-wet-DSR and CT-dry-DSR) than in CT-TPR. Labor savings of up to 60% in DSR compared with CT-TPR have been reported, with the level of savings depending on tillage, CE method, and level of mechanization. ZT-Dry-DSR saves more labor than Wet-DSR because of additional savings in land preparation.

10.6. Is direct-seeded rice economically attractive to farmers?

Farmers have perfected puddling and transplanting over time and are reluctant to try alternatives. However, economics play an important role in the decision making of farmers. Trials that are largely conducted by researchers clearly show economic advantages in DSR over puddled transplanting. Overall, based on 77 studies, DSR compared with CT-TPR had a lower cost of production by US\$22–80 ha^{-1} and savings in production costs increased in the following order: ZT-dry-DSR > Bed-dry-DSR > CT-dry-DSR ≥ CT-wet-DSR > CT-TPR. Overall, except for Bed-dry-DSR, all DSR methods resulted in US\$30–50 ha^{-1} higher economic returns than CT-TPR, but with a lower cost of production.

10.7. How does direct-seeded rice influence greenhouse gas emissions?

Well-managed studies demonstrate reductions in methane emissions in DSR (8–92%) compared with CT-TPR, with the greatest reductions occurring in Dry-DSR. These reductions in methane emissions are largely due to the avoidance of standing water in fields with direct seeding. However, several studies suggest two- to sixfold increases in N_2O emissions when shifting to direct seeding, especially with ZT-dry-DSR. A complete picture of the influence of alternative tillage and CE practices on three GHGs (CH_4, N_2O, and CO_2) in terms of GWP is lacking. It is expected that changes in tillage, especially residue, water, and N management, will have a significant impact on all the GHGs. Baseline data are urgently needed to develop improved management practices that are more environmentally friendly. Limited studies indicate that ZT-dry-DSR compared with CT-TPR has potential to reduce GWP by 20–44%.

10.8. What plant traits are the most important for optimizing direct-seeding systems?

Relatively little work has targeted selection and breeding of rice for direct seeding, especially under zero tillage in Asia. Generally, rice varieties bred for puddled transplanting are used in direct seeding. The lack of suitable varieties is a major constraint to achieving maximum potential of direct seeding. The traits that are likely to be most helpful for direct seeding include (1) anaerobic seed germination and tolerance of early submergence for quick CE, (2) high seedling vigor with faster leaf area development (semierect leaves with high specific leaf area) during the early vegetative stage for weed suppression, (3) erect leaves with low specific leaf area and high chlorophyll content for high crop growth during the reproductive phase along with high remobilization ability for higher spikelet fertility, (4) a strong, thick, and sturdy culm with long and heavy panicles positioned at lower height for lodging resistance, and (5) high genetic yield potential with high input use efficiency under DSR.

10.9. What have we achieved and what is still needed for attaining maximum potential of direct-seeded rice?

Realizations that (a) optimal plant architecture in DSR could be critical to the success of DSR, just as it has been for puddled transplanting, and (b) the importance of rapid emergence and subsequent good establishment during the early stage of rice growth have been important developments in our thinking process. This has led to the development of management practices that enhance stand establishment, including land leveling, seeding (depth, density, distance) with residue, irrigation, and weed control. Seeding at an optimal depth and distance has not only reduced the seed rate from 80–200 kg ha^{-1} to around 25 kg ha^{-1} but has also helped in overcoming spikelet sterility and lodging problems. Both agronomic management and a suitable variety with appropriate traits are needed to achieve maximum potential under DSR. Much research and many adoptive evaluations carried out during the past decade have provided management options, including improved drills to precisely place seed and fertilizer. We are making good progress in managing weeds using integrated approaches. However, additional research is needed in weed management, including (1) monitoring shifts in weed flora, (2) developing management strategies for emerging problems of weedy rice, (3) identifying new herbicides/tank mixtures with wide-spectrum weed control ability, (4) identifying vulnerabilities in weed life cycles through analysis of weed population dynamics under reduced till/ZT conditions, and (5) developing integrated strategies to minimize/avoid/delay the development of herbicide resistance in weed populations. Although refinements in agronomy and management will continue to be important, targeting varietal improvements in rice under DSR is likely to crucial for improving the potential of direct seeding.

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