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INVITED REVIEW

Potential benefits of dry direct seeded rice culture: A review

Md Moshiur Rahman[1*]

[1]Department of Agronomy, Bangladesh Agricultural University, Mymensingh, Bangladesh

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*Corresponding Author
Md Moshiur Rahman
rahmanag63@yahoo.com

ABSTRACT

Puddled transplanting is the major system of rice cultivation in many parts of the world. Transplanting system provides a high and stable yield. It is labour intensive and requires huge amount of irrigation water (1500-2000 mm). The increasing scarcity of irrigation water and labour acted as a major driver to the adoption of the wet direct seeding system in many Asian countries. Wet direct seeding saves substantial amount of labour but it has very low water saving potential. Dry direct seeding is another rice establishment method that has potential to save both water and labour in rice culture. Seedling raising, puddling and transplanting of seedling into the puddle are omitted in the dry direct seeding system, rather primed seeds are directly sown on the dry cultivated land by hand or seeder or directly by seeder without tillage. Direct seeding contributes to saving of 50% labour requirement in crop establishment. The labour saving could be even more if seeding is done by machineries. Dry direct seeding gives comparable or even higher yield than that of puddle transplanted rice. It reduces greenhouse gas emission, buildup of arsenic and other heavy metals and improves soil health compared with the conventional system. Dry direct seeded rice based cropping system offers the scope of increasing cropping intensity and diversity and farm income. Yield decline in dry direct seeded system has been reported elsewhere and the reduction of yield was mainly related with inadequate agronomic management and under continuous mono-crop upland condition. However, trials at farmers' field in Bangladesh proved that dry direct seeded rice can give better harvest than the conventional puddle transplanted rice with proper agronomic management. The adoption of dry direct seeded rice culture in Bangladesh is mainly constrained by the present irrigation water sharing system and unavailability of good quality seeding machineries. The present review focuses on the effect of dry direct seeded rice on water requirement, yield performance, cropping intensity and diversity, soil physical and chemical properties, greenhouse gas emission, labour and economic issue so that dry direct seeding can be used as a tool for increasing crop productivity with less water with minimal adverse effect on soil and environment.

Keywords: Puddle transplanted rice, flood irrigation, wet direct seeded rice, crop intensification, greenhouse gas emission

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1 Introduction

Rice is the staple food for more than half of the world's population (IRRI, 2009). Rice is grown on 161 million hectares of land with an annual production of about 678.7 million tons of paddy (Statista, 2019). About 90% rice of the world rice is grown in Asia (Muthayya et al., 2014). Rice provides 30-75% of the total calories intake by more than 3 billion Asians (von Braun and Bos, 2004). The population of the world is increasing and the food demand is also increasing. Thus, food production needs to be increased by 70% to meet up the global food demand by 2050 (Muthayya et al., 2014). The horizontal expansion of rice area is limited in the near future due to decrease of agricultural land. Thus, the additional rice production should come from the increase of productivity. The major challenges towards achieving the increased production include scarcity of water and labour, increased wage rates and production cost, soil and environmental degradation. Transplanting of seedling into the puddled land is the major method of rice establishment in Asia. The advantages of the traditional system include increased nutrient availability (e.g. iron, zinc, phosphorous) and weed suppression. Puddling is a tillage practice of mixing soil and water by which a hard pan is developed below the plow zone to reduce soil permeability under the conventional planting. High loss of water occurs during the puddling process, surface evaporation and percolation. Traditional puddle transplanted-flood irrigated low land rice culture uses more than 80% of the developed freshwater resources used for irrigation purposes of which about half is used for rice production (Dawe et al., 1998).

Transplanting system provides a high and stable yield. Looming water crises and increasing labor costs are the challenges being faced by the rice growers in the traditional transplanting system.Tuong and Bouman (2003) reported that 39 million ha of irrigated rice may suffer from 'physical water scarcity' or 'economic water scarcity' by 2025 in Asia. It is also reported that South Asia may experience 30% decline in agricultural production by 2050 due to water shortage (Hossain and Siddique, 2015). The withdrawal of huge ground water for irrigation and industrial uses has led to diminished river flow, lowering ground water tables, land subsidence and formation of cracks and sinkholes, and causing serious threats to the environment (BADC, 2006). Both underground and surface water in Bangladesh is also shrinking and will become the most limiting factor in future. The lowering of water table leads to more costly pumping of groundwater and increased cost of production (BADC, 2006). Sometimes labour may not be available at the right time for transplanting. Recently, labour scarcity has been seen in many countries, especially in the peak period of transplanting. Due to industrialization and urbanization in recent years, the shortage of labor in has aggravated the situation resulting in an increase in labour costs in agriculture, which, in turn threatens the sustainability of the traditional rice planting system. Moreover, rice cultivation in continuous flooded wetland system causes arsenic toxicity and also contributes to global warming, as it is the largest source of methane emission (Neue, 1993). At the face of the water and labour scarcity and related environmental, human health and social issues demands the alternate rice establishment technology that can maintain or increase yield while using less labour and water.

The water scarcity, economic factors and recent changes in rice production technology have improved the desirability of direct-seeding methods (Pandey and Velasco, 2002). Direct seeding method includes dry direct seeding and wet direct seeding. Wet direct seeding has been adopted in many Southeast Asian countries in response to increased labour scarcity and wage rates. In contrast, the areas where scarcity of both labour and irrigation water is prominent, dry direct seeding is the best alternative to conventional practice for sustaining rice production (Pandey et al., 2002; Gathala et al., 2014). However, the productivity of direct seeded rice is similar to that of transplanting system and even it fetches higher economic return (Mitra et al., 2005). Against the backdrop of declining water resources and reduced availability of labor, the conventionally flooded rice system is losing its sustainability and economic viability (Bhushan et al., 2007). The decreasing water table, increasing costs of diesel and electricity and climatic changes have further aggravated the problem. Dry direct seeding (DDS) (Fig. 1) is a new system of rice cultivation where rice seed is sown into the dry cultivated land at optimum moisture for seed germination (Joshi et al., 2013). This method ensures sowing of much more area in less time with the same available farm power and labor than the conventional system. There is a savings of water required for puddling and also during the period from sowing to late tillering stage. Farmers may accept DDS system as an attractive alternative to the traditional transplanted conventional systems for dry season rice cultivation as it reduces irrigation and labour costs, and gives higher yield.

The present review focuses on effects of dry direct seeding on crop yield, water requirement, labour saving, soil health and environmental quality. It is also intended to explore the potential of dry direct seeding as a climate smart solution to water and labour scarcity in rice culture and to use it as a means for protecting soil and environmental degradation.

2 Water resources and irrigation scenario

Water is becoming a scarce resource globally. Irrigated agriculture consumes about 70 and 90% of the

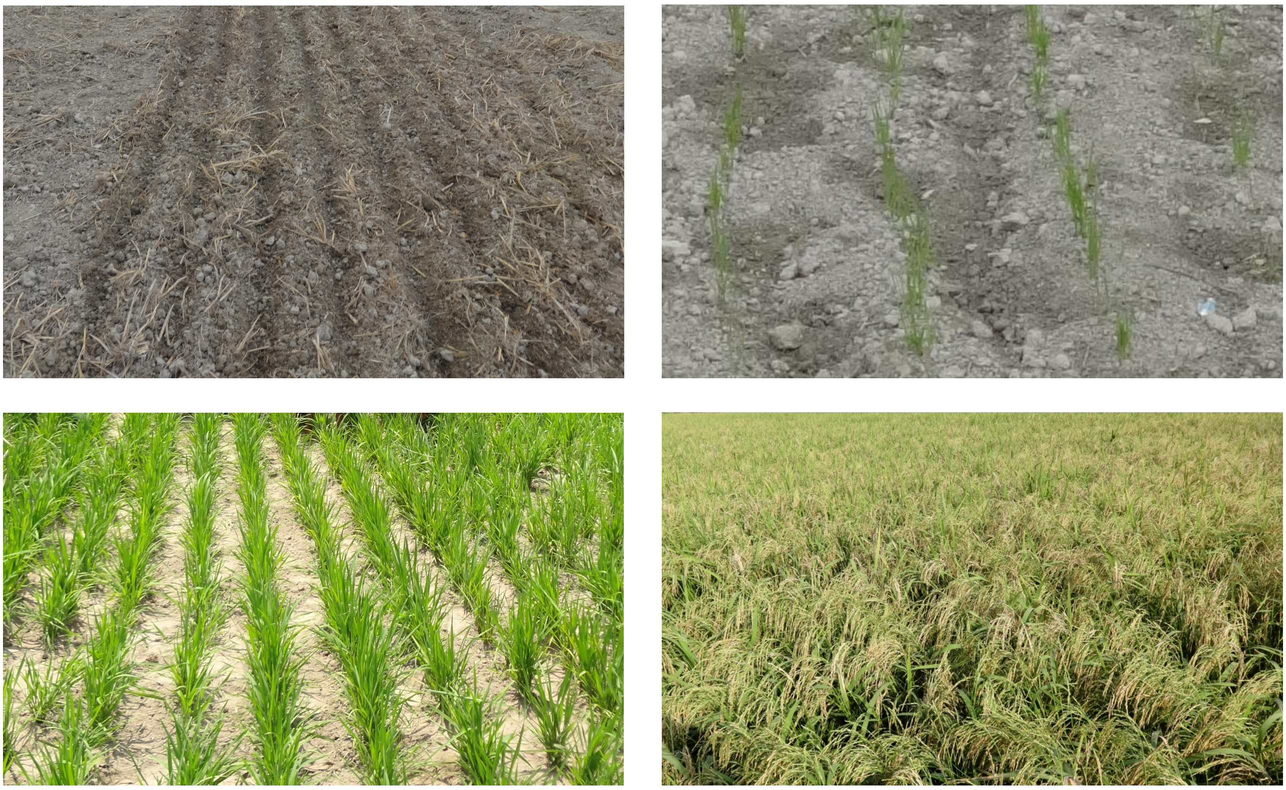

Figure 1. Different stages of dry direct seeded rice cultivation

total freshwater withdrawal globally and in Asia, respectively (Hoekstra and Chapagain, 2006; Molden et al., 2007; Tabbal et al., 2002). The share of water in agriculture decreased from 98% in 1900 to 80% in 2000 in Asia and is most likely to decline in future (Kumar and Ladha, 2011). The share of water for agriculture is declining fast as because of falling of groundwater table, deterioration of water quality due to chemical pollution, salinization, inefficient irrigation systems, and competition with non-agricultural sectors (domestic, industrial and environmental). The decline in water share for agriculture warrants the need of development and deployment of highly water use efficient crop production technologies (Fig. 2).

Groundwater table declined in many rice growing countries of the world mainly due to heavy extraction of water for irrigation in rice (Mollah, 2017) (Fig. 3). For example, the decline of groundwater table in India is 0.5–2.0 m per year (Singh and Singh, 2002; Tuong and Bouman, 2003), North China Plain is 1–3 m per year (Bouman et al., 2007; Bouman, 2007; Liu et al., 2001; Liu and Xia, 2004), in the northwestern region of Bangladesh is 0.1–0.5 m per year (Shamsudduha et al., 2009; Dey et al., 2013). The decline of water table is making the use of STWs tapping shallow aquifers unsustainable for intensive dry season irrigation The decline of water table of 0.33 m yr^{-1} in north eastern India caused a net loss of 109 km^3 of groundwater during the period from 2002 to 2008 (Rodell et al., 2009). In Asia, about 13 million ha of wet season rice and 2 million ha of irrigated dry season rice may 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).

Rashid (2002) reports that although groundwater table declines gradually day by day due to increasing demand for discharge in Bangladesh but the aquifer recharges after the monsoon if sufficient rainfall occurs. Dry season groundwater irrigation over seven month period depends on adequate recharge in the five-month monsoon period. Due to heavy use of groundwater the shallow wells are going dry by the end of the dry season in Bangladesh. In the dry season growing areas, more than 90% of the total irrigation water is supplied through groundwater in Bangladesh. The groundwater irrigation expansion has led to decline in water table in different parts of the country and the groundwater quality is deteriorating. The over exploitation of groundwater irrigation has created a serious imbalance in groundwater recharge and discharge in many locations. Currently about 4.2 million ha of land is irrigated by groundwater whereas only 1.03 million ha by surface water. The area irrigated by surface water declined from 76% in 1981 to 23% in 2012, while the area irrigated by groundwater has jumped to 80% from 16% in Bangladesh (BADC, 2013).

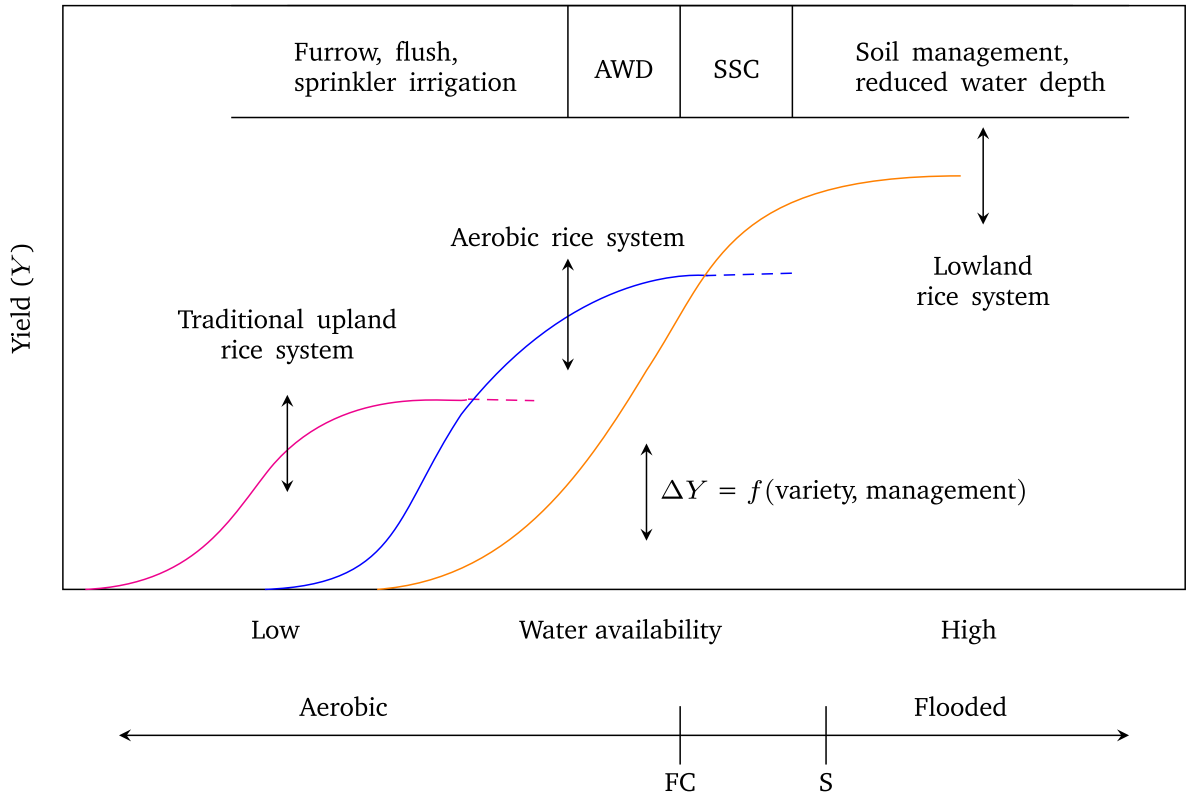

Figure 2. Available technologies of rice cultivation based on water availability. AWD = Alternate wetting and drying, SSC = Saturated soil culture, FC = Field capacity, S = Saturation point. Reproduced from Tuong et al. (2005).

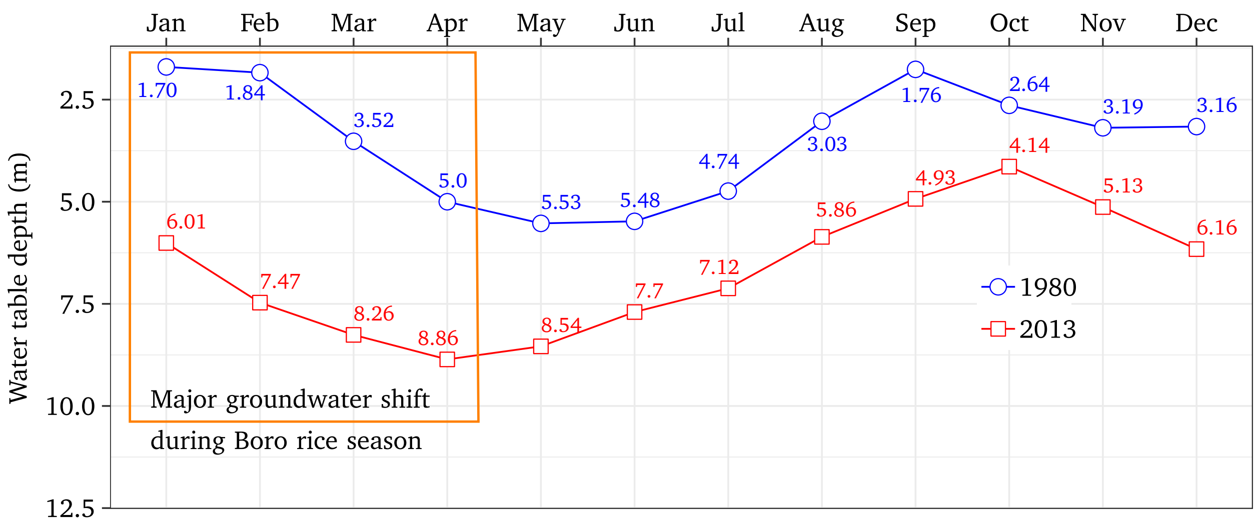

Figure 3. Groundwater level shift from 1980 to 2013 due to Boro rice cultivation in Dhamrai, Dhaka. Reproduced from Mollah (2017).

The energy cost for diesel and electric operated DTWs is 41% and 34% of the total production cost, respectively. The cost of irrigation for dry season rice has increased from BDT 4080 ha^{-1} in 1989 to over BDT 11280 ha^{-1} in 2011 due to increase of price for diesel and electricity (Dey et al., 2013). The increased irrigation costs would reduce farmer's net incomes, threatening the economic foundations upon which boro rice production is based. The water scarcity and high irrigation is making rice production difficult and unsustainable that warrants the exploitation of alternative rice production methods, which inherently require less water and are more efficient in water use (Balasubramanian and Hill, 2002). Dry direct seeding could be considered as a water efficient technology having some advantages over puddle transplanted system (Bhuiyan et al., 1995; Dawe, 2005; Humphreys et al., 2005; Tabbal et al., 2002).

3 Water requirements for rice culture

Rice is the major user of freshwater (Barker et al., 1999; Carriger et al., 2007; Tuong et al., 2005) and consumes about 50% of total irrigation water used in Asia (Barker et al., 1999; Hoekstra and Chapagain, 2006; Bouman, 2007). The seasonal water requirement in rice field combines the requirement of water for land preparation, the amount required for evaporation, transpiration, seepage and percolation losses during the growth of the crop. The actual water requirement for rice is almost equal to the evapotranspiration demand because only very small amount is actually retained in the plant. The other requirements are the loss for land preparation, loss through seepage and percolation in the crop root zone area during the crop growing period (Hafeez et al., 2007).

Transplanted-flooded rice leads to high losses of water through puddling, surface evaporation and percolation (Farooq et al., 2011). In China, transplanted flooded rice is the major production system of rice and nearly 95% of the rice is grown under such conditions with prolonged periods of flooding (Peng et al., 2009). The water requirement for rice depends on growing season, variety, soil, climatic condition, the depth of irrigated water and water management practices. Water demands for the growing period of rice ranges from 470 to 2650 mm (Sudhir-Yadav et al., 2011). The water requirement during the whole growing season for dry direct seeding and transplanting system in dry season are 729 and 954 mm water, respectively (Khan, 2008) while the rice production in wet season requires 723 mm water (De Datta, 1981). Bouman et al. (2005) reported that the water use in rice is 1300–1500 mm for dry season and 1400–1900 mm for the wet season in the Philippines. The water input for land preparation (puddling) is 150–250 mm (Tuong, 2000), for evapo-transpiration is 400-700 mm (600–700 mm in dry season and 400–500 mm in the wet season), and unavoidable losses due to seepage and percolation is 100–500 mm for heavy clays and 1500 –3000 mm for loamy and sandy soils. Total irrigation water requirement for dry season rice is 1500 to 2000 mm of which 500 to 550 mm is required for evapo-transpiration and rest is lost due to percolation and runoff, and thus, 60 to 75% of the total irrigation water is unavailable for the rice crop. The seasonal water input for rice in India ranges from 1560 mm in clay loam soil to 2262 mm in a sandy loam soil, the variation mainly due to deep percolation losses. The water requirement for rice in dry season is 1220–1440 mm in Barind (Rahman et al., 2013) (Table 1) and 461.02 mm in Old Brahmaputa Flood plain areas of Bangladesh (Hoque et al., 1994). Peng et al. (2006) reported that water requirement for rice was 747 mm in dry season. The cultivation of flooded lowland rice required about 1300 mm of water while dry direct seeded rice used only 470 to 644 mm. The rice under lowland flood irrigation system generally requires on an average 2500 L of water, ranging from 800 to more than 5000 L to produce one kg of rough rice (Bouman and Tuong, 2001; Bouman, 2009). Dry direct seeded management eliminated water losses associated with puddling and reduced losses due to evaporation and percolation during the crop growth period (Castaneda et al., 2002). Thus, dry direct seeded rice consumes 50% less irrigation water than traditional lowland rice (Lampayan et al., 2004).

4 Yield performance of DDS rice

Dry direct seeded rice gives higher or similar yield to that of conventional puddle transplanted flood irrigation rice. Rahman et al. (2012) compared the yield performance of two rice varieties *viz.* BRRI dhan29 and BRRI dhan45 under five systems of cultivation *viz.* puddle transplanted with conventional flood irrigation (PTR–CI), puddle transplanted with alternate wetting and drying irrigation (PTR–AWD), system of rice intensification (SRI), wet direct seeding (WDSR) and dry direct seeding (DDSR) over two consecutive dry seasons (2007–2008 and 2008–2009) at Old Brahmaputra Floodplain of Bangladesh. The results revealed that dry direct seeded method gave higher yield among the different methods of cultivation practiced. Rahman and Masood (2014) evaluated the yield performance of these two rice varieties under three cultivation systems *viz.* puddle transplanted with conventional flood irrigation (PTR–CI), puddle transplanted with alternate wetting and drying irrigation (PTR–AWD) and dry direct seeding (DDSR) system at four diverse locations of Old Brahmaputra Floodplain, Level Barind Tract, North Eastern Barind Tract and Modhupur Tract of Bangladesh in two consecutive dry seasons (2009–10 and 2010–11) (Table 2). The yields of rice varieties were significantly higher in dry direct seeded system using only 432 mm wa-

Table 1. Frequency and amount of irrigation water applied in different systems of rice cultivation in farmers' field at four locations of Bangladesh in 2010–11

System †	Dinajpur		Rajshahi		Tangail		Netrokona	
	Freq.	Amount (mm)‡	Freq.	Amount (mm)	Freq.	Amount (mm)	Freq.	Amount (mm)
PTR-CI	14	1220	16	1375	18	1390	16	1310
PTR-AWD	11	950 (22%↓)	12	1020 (25%↓)	11	1020 (26%↓)	12	980 (25%↓)
DDSR	6	500 (59%↓)	7	560 (59.2%↓)	7	550 (60.4%↓)	8	520 (60.3%↓)

† PTR–CI = Puddled transplanting with conventional irrigation, PTR–AWD = Puddled transplanting with alternate wetting and drying, and DDSR = Dry direct seeded rice; Value with ↓ in a parenthesis indicates the amount (lower) of irrigation (%) needed in comparison to PTR–CI system in the respective site; Source: Rahman et al. (2013).

Table 2. Yield of BRRI dhan29 (t ha^{-1}) in different systems of rice cultivation in farmers' field at four locations of Bangladesh

System †	Dinajpur		Rajshahi		Tangail		Netrokona	
	2009–10	2010–11	2009–10	2010–11	2009–10	2010–11	2009–10	2010–11
PTR-CI	6.2	7.0	6.8	7.6	3.9	5.4	6.9	8.1
PTR-AWD	6.7 (7%↑)	7.5 (6%↑)	7.0 (6%↑)	7.9 (5%↑)	4.0 (4%↑)	5.3 (1%↓)	7.4 (7%↑)	8.4 (4%↑)
DDSR	7.3 (17%↑)	8.1 (15%↑)	8.3 (21%↑)	8.6 (14%↑)	4.2 (9%↑)	6.1 (14%↑)	7.9 (14%↑)	8.8 (9%↑)

† PTR–CI = Puddled transplanting with conventional irrigation, PTR–AWD = Puddled transplanting with alternate wetting and drying, and DDSR = Dry direct seeded rice; ‡ Value with ↓ or ↑ in a parenthesis indicates the yield (lower or higher in %) in comparison to PTR–CI system in the respective site; Source: Rahman et al. (2013).

ter against puddled transplanted system using 1210 mm irrigation. The yield improvement in DDS was mainly attributed to the increase in panicle density in DDSR than PTR–CI. Liu et al. (2014) compared the yield of three rice varieties under dry direct seeding and traditional puddled transplanted systems at Hubei Province of China. They found no significant yield variation between the two systems for any of the three varieties. Results from northern China showed that dry direct seeded rice gave comparable yield to the transplanted rice (Pandey and Velasco, 2002). Statista (2019) reported that dry direct seeded rice produced 10.3 t ha^{-1} grain yield in Mossouri, USA with only 750 mm water input. Again, report from China revealed that dry direct seeded rice gave 22% higher yield than puddle transplanted flooded rice (Lun, 2008). The above literatures clearly states that dry direct seeding system gives higher or comparable yield to that of conventional puddle transplanted flood irrigated rice.

In contrast, many reports shows that dry direct seeding gives lower yield than conventional puddle transplanted rice. Luo et al. (2003) found that dry direct seeded rice gave lower yield (4.7–5.3 t ha^{-1}) compared with flooded lowland rice (8.8 t ha^{-1}). In Brazil, Guimaraes and Stone (2000) reported that under continuous mono-cropping the yield of dry direct seeded rice declined while high yield could be sustained when dry direct seeded rice is grown once in four crops. Similar results were reported by George et al. (2002). Ventura et al. (1981) reported a rapid yield decline under continuous upland rice cropping in the Philippines. De Datta (1981) observed that the yield of a lowland variety IR20 reduced to 3.4 t ha^{-1} under dry direct seeded conditions from about 8 t ha^{-1} in flooded condition although water saving was 55% in dry direct seeded soil at IRRI. Kumar and Ladha (2011) observed 9.2 to 28.5% yield decline in dry seeded rice than conventional puddle transplanted rice in different Asian countries. Peng et al. (2006) found 8 to 69% yield reduction in dry direct seeded than flooded rice at IRRI in the Philippines. The yield of dry DSR reduced from 15% in 2001 to 69% in 2004 in dry season (DS) and from 23 to 50% in wet season (WS) in north western IGP compared with puddle transplanted one. Bouman et al. (2002) reported that sink size (spikelets m^{-2}) contributed more to the yield gap between dry direct seeded and flooded rice than grain filling percentage and 1000-grain weight. They further reported that flooded rice produced more panicles with more spikelets panicle^{-1} than dry direct seeded rice. The yield decline in dry seeding could be related to the build-up of nematodes and soil pathogens and also to poor weed control (Lafitte et al., 2002). In addition, a number of reasons could be responsible for yield penalty in dry direct seeding system such as the poor stand establishment, inadequate weed control, higher

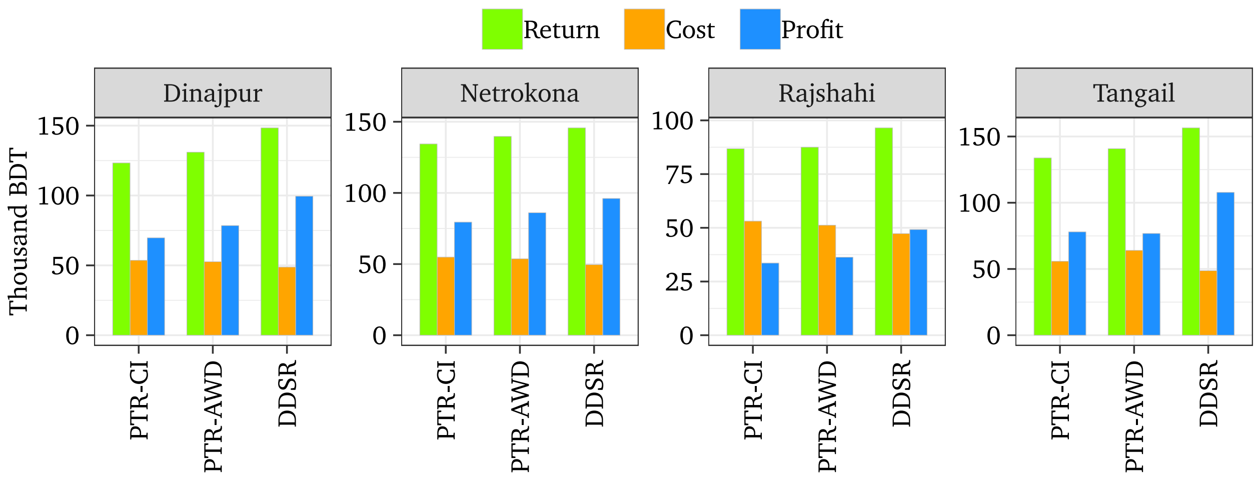

Figure 4. Cost and return (in '000' Tk) of rice cultivation (variety BRRI dhan29) under different systems at farmers' field in four locations of Bangladesh. PTR–CI = Puddled transplanting with conventional irrigation, PTR–AWD = Puddled transplanting with alternate wetting and drying, and DDSR = Dry direct seeded rice. Data source: Rahman et al. (2013)

spikelet sterility, and insufficient knowledge on water and nutrient management (Kumar and Ladha, 2011). Therefore, the success of dry direct seeding technology as an alternative to puddle transplanting system mainly depends on proper crop management.

5 Labour and economic issues

Land preparation (puddling) and crop establishment (seedling raising and transplanting) under conventional system requires large amount of labour. Recent industrial development has increased the labour demand in the non-agricultural sectors leading to reduced labour availability for agriculture (Dawe, 2005). The labour force in agriculture is declining at 0.1–0.4%, with an average of 0.2% in Asia. The labour force involved in agriculture declined from 45% in 1961 to 25% in 2008 in Bangladesh. It is noticed that most people prefer non-agricultural work under the present changing socio-economic environment. The decline in labour availability leads to increase in wage rate even in many Asian countries. In Bangladesh the wage rate per labour per days was 20 BDT in 1980 which is now 380 BDT. Traditional transplanting requires 35–40 person-days ha^{-1} but dry direct seeding needs about 30–35 person-day ha^{-1}. Thus, dry direct seeding could be practice to reduce labour use in rice establishment.

Labour requirement in dry direct seeding is lower than conventional puddled transplanting system because dry direct seeding avoids nursery raising, seedling uprooting, puddling operation and transplanting and thus reduces the labour requirement. Depending on the season, location, and management practices used, DSR systems can save total labour requirements by 11–66% (Kumar et al., 2009) and irrigation water need by 35–57% (Bhushan et al., 2007; Jat et al., 2009) compared with puddled transplanted rice. Saharawat et al. (2010) reported that the human labour utilization over the whole cropping season of 56 d ha^{-1} for DSR, 13% lower than for PTR. A study conducted at Ludhiana (Punjab) found a net labour cost saving of Rs 1250 ha^{-1} with DSR (Gill and Dhingra, 2002). According to Pandey and Velasco (2002), low wages and adequate water favour transplanting, whereas, high wages and low water availability favour direct seeded rice (DSR). Wang et al. (2002) stated that dry direct seeded system is a new way of cultivating rice that requires less water than lowland rice. DSR is advantageous to mechanization and brings additional benefit from being labour and cost-effective (Khade et al., 1993). For example, a VMP machine can sow one hectare of land per day requiring 2500–4000 BDT while manual transplanting will require about 15000–20000 BDT ha^{-1}. Dry direct seeded rice requires less labour than lowland rice and can be highly mechanized. 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). Further developments of dry direct seeded rice need to concentrate on continued breeding and the development of sustainable and farmer-acceptable crop management strategies. Rahman and Masood (2014) reported that the total production cost in different locations of Bangladesh was the highest for PTR–CI system and the lowest for DDSR system. It was noted that DDSR required about 5.5 and 3.4% less cost than PTR–CI and PTR–AWD systems, respectively. The cost reduction was achieved mainly from labour saving for seedling raising, uprooting and transplanting as well as from irrigation (Fig. 4). (Mitra et al., 2005) reported that DDSR saved about 11.2% production cost over puddled transplanted rice. Wong and Morooka (1996) recorded about 29% cost saving in DDSR system than puddle transplanted rice. Further cost saving could be achieved by reducing cost of weeding by adopting different low cost weed management.

6 Green house gas emission issue

Agricultural activities contributes to the emission of three important greenhouse gases leading to the global warming– carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The share of agriculture to the emission of N_2O, CH_4, and CO_2 are 60%, 39%, and 1%, respectively (OECD, 2001). Rice based cropping system plays the major role to the emission of greenhouse gases (Fig. 5). Conventional flooded rice culture with puddling and transplanting is the major source of CH_4 emissions as prolonged flooding creates an anaerobic soil conditions accounting for 10–20% (50–100 Tg yr^{-1}) emission (Houghton et al., 1996). Methane formation depends on the metabolic activity of a group of bacteria and activity of methanogen bacteria increases in anaerobic condition. The major pathways of CH_4 production in flooded soils are the reduction of C compounds to CH_4 due to restricted oxygen supply. Anaerobic condition is the pre-requisite for the activities of methanogenic bacteria and CH_4 production. Thus, CH_4 is low under aerobic condition. In the conventional transplanted rice field standing water is kept throughout the crop growing season and thus the methane emission is higher in this case while DDSR field is not continuously submerged and therefore, CH_4 is less in the DDSR field (Joshi et al., 2013).

The amount of CH_4 emission depends on soil pH, redox potential, soil texture, soil salinity, temperature, rainfall and water management (Aulakh et al., 2001). It was found that dry direct seeded rice culture reduced 24 to 79% and 43 to 75% CH_4 emission under continuous flooded and intermittent irrigated system compared with the puddle transplanted continuous flood irrigated rice field (Kumar and Ladha, 2011). Pathak et al. (2013) reported that CH_4 emission in dry seeded field was 0.6–4.9 kg ha^{-1} and puddled transplanted field was 42.4–57.8 kg ha^{-1} in different areas of Punjab, India. Although dry direct seeding can reduce CH_4 emission under aerobic soil condition, the relatively more soil aerobic state may increase N_2O emission. N_2O is produced as by-product during soil microbial nitrification and de-nitrification processes (Malla et al., 2005), which is highly dependent on soil water status and fertilizer application. The nitrification takes place under aerobic condition (Pathak et al., 2011). N_2O emission in DDSR and PTR–CI field was 0.95 kg N_2O N ha^{-1} and 0.65 kg N_2O N ha^{-1}, respectively in Jinagsu, China (Liu et al., 2014). In India, the N_2O emission was 0.31–0.39 kg N ha^{-1} under PTR–CI which increased to 0.90–1.1 kg N ha^{-1} and 1.3–2.2 kg N ha^{-1}, in conventional tillage dry direct seeded rice and zero till dry direct seeded rice, respectively (Kumar and Ladha, 2011). Pathak et al. (2013) estimated that N_2O emission in 2009 in DDSR was 0.9–1.2 kg ha^{-1} and 0.8 to 1.1 kg ha^{-1} in PTR fields in Punjab, India while that was 2.0–2.2 kg ha^{-1} in DSR and 1.6–1.8 kg ha^{-1} in TPR in 2010. Methane emission starts at redox potential of soil below −150 mV and is stimulated at less than −200 mV (Jugsujinda et al., 1996; Wang et al., 1993). Nitrous oxide emission increases at redox potential above 250 mV (Hou et al., 2000). Therefore, water management should be in such a way that soil redox potential to be kept at intermediate range (100 to 200 mV) to minimize emission of both CH_4 and N_2O. Thus, dry direct seeding could be considered as an important technique to reduce greenhouse gas emission Corton et al. (2000); Wassmann et al. (2004).

7 Environmental and health issues

Intensive rice culture, especially in dry season, requires extraction of the more water from surface and ground water reservoirs than it is being replenished by rainfall. Withdrawal of huge underground water has led to diminished river flow, lowering ground water tables resulting costly pumping, land subsidence and formation of cracks and sinkholes, and causing serious threat to the environment by development of salinity problems and heavy metal pollutions of soil. The huge uplifting of underground water for irrigation in dry season rice is also causing serious health hazard by accumulating heavy metal in the water aquifers. Actually, the over-use of irrigation water for dry season rice cultivation is causing not only threat to the environment but also causing serious threat to the human health. High arsenic (As) concentration is mainly limited to the groundwater from shallow aquifers with depth less than 100 m (Qureshi et al., 2014). It is estimated that 24% of the groundwater irrigated dry season rice area in Bangladesh is using water containing >50 m μg As L^{-1} and about 7% area is irrigated with water containing >100 μg As L^{-1} (Ross et al., 2006). Neue (1993) reported that rice cultivation in continuous flooded wetland system causes As toxicity. Bangladesh government has given top most priority on remediation of arsenic and heavy metal pollution to protect people from arsenic and other heavy metal toxicity (BADC, 2006). Irrigation with As laden water in dry season rice may pose serious threat to human health as it increases As concentration in rice grain and also increases accumulation of As in the soil over time (Ahmed et al., 2010; Panaullah

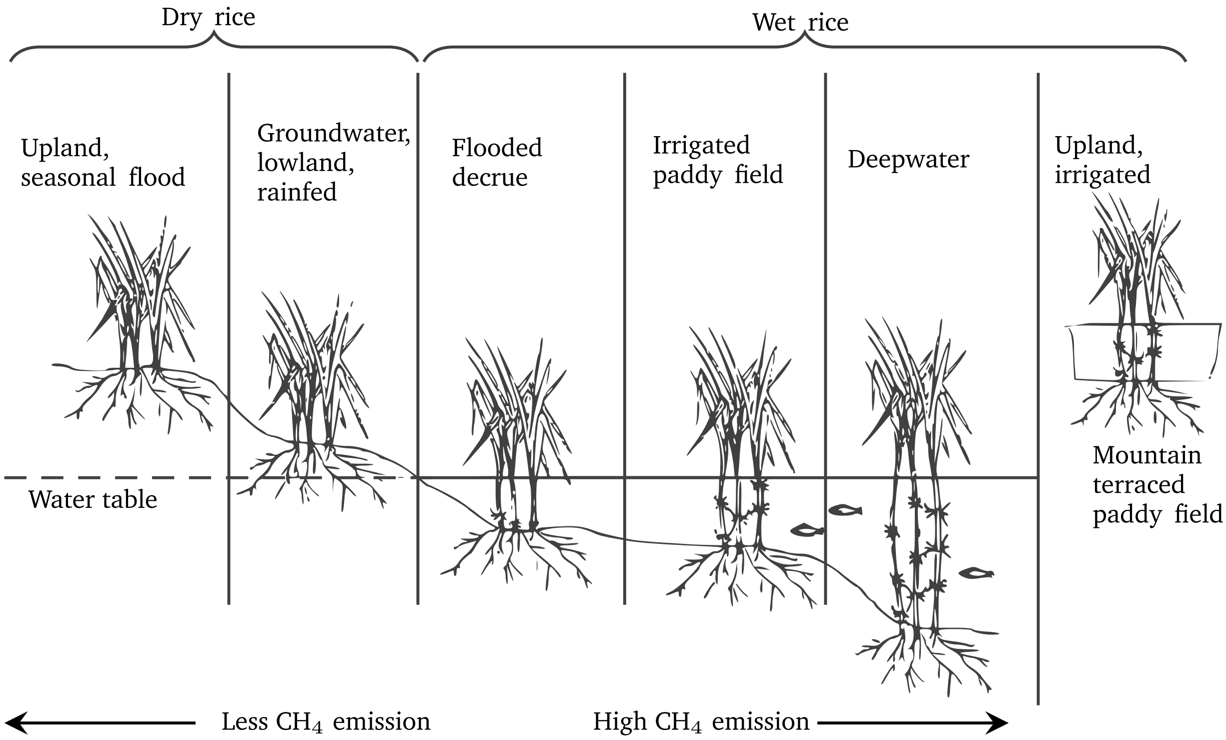

Figure 5. Methane gas emission from rice field as a function of water management in the field. The drawing was modified from Fuller et al. (2011).

et al., 2008; Dittmar et al., 2010). The increase of As in soil may be caused as inorganic As species in irrigation water are retained in soils by adsorption of mineral oxide sulphate (Duxbury et al., 2009). Accumulation of As in rice can also negatively affect rice yield (Panaullah et al., 2008; Duxbury et al., 2009) and elevate arsenic concentration in rice grain (Ahmed et al., 2010; Williams et al., 2006), posing health risks for consumers.

Water management system has significant effect on grain arsenic content in rice. Accumulation of As in rice can also negatively affect rice yield and elevate As concentration in rice grain posing health risks for consumers. It was found that aerobic (dry) condition reduces the grain arsenic content than anaerobic (flooded) condition (Daum et al., 2001). The As contamination is found when rice is grown in high land and medium high land with groundwater irrigation from shallow aquifers. Use of As contaminated irrigation water created a gradient in soil As from 10 to 60 mg kg^{-1} in a farmer's fields, reducing dry season rice yields by up to 5 t ha^{-1} under acute toxicity. High concentration of As in rice grain have been found in many parts of Bangladesh. Arsenic changes it states depending on the state of oxido-reduction of the soil. The oxidation of soil by drainage leads to the oxidation of the arsenite to the form of arsenate, that decreases the solubility, plant availability and toxicity of arsenic (Takahashi et al., 2004). Thus, water saving aerobic rice cultivation should be practiced in the arsenic affected area to get rid of the arsenic problems (Yamane et al., 1976; Maejima et al., 2008; Sarkar et al., 2012).

8 Crop Intensification and diversification

Crop intensification and diversification is another benefits of dry direct seeded rice in addition to its potential benefit in saving of water and labour in rice cultivation. Incorporation of one more crop in the existing cropping pattern is another factor in adoption of this technology. For example, early establishment and short duration varieties allowed harvesting of dry DDS rice early to permit growing of one or two more crops in the rotation in Mekong Delta in Vietnam and Iloilo in the Philippines, thus DDSR allowed double or triple cropping instead of single crop of transplanted rice (Pandey and Velasco, 2002; Van My et al., 1995). The availability of high yielding short duration rice varieties and new herbicides for weed control has largely contributed to this shift in rice culture (Arefin et al., 2018; Rahman et al., 2017; Juraimi et al., 2013; Anwar et al., 2012a,b; Mortimer et al., 2008; Pandey and Velasco, 2002). T. Aman rice – Fallow – T. Boro rice is the major cropping pattern in Bangladesh however, T.aman rice – mustard – Boro rice has been introduced as new resource-conserving production techniques to meet the challenge of productivity enhancement, ensure environmental safety and conserve natural resources (Mondal et al., 2015; Nasim et al., 2018). In T. aman rice – Fallow – T. Boro rice pattern farmers generally wait up to mid-January for planting of boro rice. The climate condition in Bangladesh is suitable for mustard cultivation and could be grown in winter season after T.aman rice in fallow lands. Usually farmers keep land fallow after T.aman harvest till coming boro sowing. On such lands farmers can easily grow mustard in winter season as an additional crop and without disturbing their traditional rice cultivation (T.aman rice – Fallow – Boro rice). Many other short duration winter crops such as mustard, potato, pea cabbage, cauliflower, tomato, broccoli, field pea, garden pea, soybean and other vegetables can also easily be grown in between two rice crops to increase productivity and diversity.

Intercropping is another way of increasing cropping intensity and diversity. It is an agricultural practice where two or more crops are grown in the same land area at the same time. It can increase total farm income through efficient use of agricultural resource. In case of dry direct seeding, after seeding of the rice seed, there is less competition of crop stands for the early 30–50 d when weed is the main competitor with rice plants. The intercropping during early crop growth period can reduce the weed competition and can be a strategy for efficient weed management through non-chemical methods. Sarma and Shyam (1992) reported that intercropping gave higher equivalent yield than rice alone. Rabeya et al. (2018) reported that intercropping of different vegetables with dry direct seeded boro rice cv. BRRI dhan28 increased net return and paved the way to increase cropping diversity.

9 Conclusions

Scarcity of irrigation water and labour and increased labour wages pose serious threats to the sustainability of rice production following the most popular conventional puddle transplanted flood rice culture. This system of rice production contributes to the emission of greenhouse gas and accumulation of arsenic in the soil. Moreover, puddling destroys the soil structure and causes negative impact on the yield performance of the subsequent non-rice crops. Moreover, irrigation for the conventional system requires huge amount of diesel and electricity and puts serious threat to the environment. At this situation, dry direct seeding could be considered as the best alternative rice cultivation system. The dry direct seeded system eliminates the need of puddling and reduces the irrigation water requirement by 60% and labour requirement. Although yield decline in dry direct seeded rice being reported by many workers, there are many reports where yield increase is found. The yield of dry direct seeded rice is mostly related to the use of proper management practices. The use of good management practices could help sustain productivity of rice in dry direct seeded system with less water. Therefore, policy formulation for development of appropriate irrigation strategy and seeding machinery would help rapid adoption of the technology.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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