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Efficient crop management strategies to improve crop resilience and crop-water productivity enhancement under direct seeded rice cultivation system in adverse climatic conditions: A review

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Abstract

The water crisis is threatening the sustainability of the irrigated rice system and food security in Asia. Our challenge is to develop novel technologies and production systems that allow rice production to be maintained or increased in the face of declining water availability. This review paper introduces principles that govern technologies and systems for reducing water inputs and increasing water productivity, and assesses the opportunities of such technologies and systems at spatial scale levels from plant to field, to irrigation system, and to agro-ecological zones. We concluded that, while increasing the productivity of irrigated rice with transpired water may require breakthroughs in breeding, many technologies can reduce water inputs at the field level and increase field-level water productivity with respect to irrigation and total water inputs. Most of them, however, come at the cost of decreased yield. More rice with less water can only be achieved when water management is integrated with direct-seeded rice (DSR) technique is gaining popularity because of its low input demand compared to puddle transplanted rice (PTR). It is done by sowing pre-germinated seeds in puddled soil (wet-DSR), standing water (water seeding), or dry seeding on a prepared seedbed (dry DSR). Alternative tillage and rice establishment options should aim at less water and labor to produce similar or improved yields compared with traditional puddled-transplanted rice cultivation. DSR requires less water and labor (12–35%), reduces methane emissions (10–90%), improves soil physical properties, involves less drudger and gives comparable yields. The AWD technology required about 22% less water compared to the continuous standing water irrigation system. Depending on the rice varieties and season of the rice cultivation, greenhouse gas emissions were 13%–41% less under AWD compared to continuous standing water. Water savings using alternate wetting and drying (AWD) ranged from 42.8 to 53.7% of total water input in comparison with continuous flooding (CF), without yield loss, but there was little difference in water input among AWD treatments. Due to shorter duration of growth in the main field, water input with 30-d-old seedlings was lower than with younger seedlings, but with a corresponding yield loss. Total water productivities in AWD treatments were higher than those with CF. Moreover, non-puddled transplanting of rice saves 35% of the net life cycle greenhouse gases (GHGs) compared with the conventional practice by a combination of decreasing greenhouse gases emissions from soil. Dry-seeded rice technology offers a significant opportunity for conserving irrigation water by using rainfall more effectively. The future of rice production will therefore depend heavily on developing and adopting strategies and practices that will use water efficiently in irrigation systems. This review paper emphasizes the need for integrating various water-saving measures into practical models and for conducting holistic assessments of their impact within and outside irrigation systems in the water basin.

Keywords: Direct seeded rice, greenhouse gas emissions, crop establishment

Introduction

The sustainability of land and water resources is fundamental to ensure food security and livelihood opportunities for a rapidly growing population (FAO, 2020; Hogeboom *et al*., 2020) [26]. It becomes even more compelling to do so with a minimal water footprint given that the world's population is expected to touch 9.5 billion by 2050 (Gerten *et al*., 2020) [74]. Changes in land use and growing land degradation are affecting crop yields across the globe (Meena *et al*., 2020) [75]. While there is limited scope to explore available natural resources as current utilization has crossed permissible thresholds, there are opportunities to enhance resource use efficiency to meet future food and fodder demands (Niu *et al*., 2019) [83]. Globally, rainfed agriculture occupies 80% of the land and contributes about 60% to food production.

The remaining 20% of land under irrigated agriculture supports about 40% of the food supply and contributes to food self-sufficiency in a number of developing countries (FAO, 2017). However, current resource use efficiency both in rainfed and irrigated systems is much below the achievable potential at the global level (Gerten *et al*., 2020) [74]. Both systems have their unique challenges (Strassburg *et al*., 2020) [76]. Rainfed systems have been experiencing physical water scarcity and land degradation (Mezegebu *et al*., 2020; Abera *et al*., 2020) [77, 1]. Therefore, a significant area of land is left fallow or underutilized due to no availability of supplemental irrigation (Singh *et al*., 2014) [78]. On the contrary, irrigated systems are subject to indiscriminate use of available resources that lead to poor resource use efficiency (Meena *et al*., 2019) [79].

According to one estimate, to produce 1 kg of rice, 2000–5000 L of water are required (Caine *et al*. 2019) [11]. The increased competition of accelerated urbanization and industrial development further limit freshwater resources for rice production. Therefore, the need for "more rice with less water" is the need of the hour for global food security (Maneepitak *et al*. 2019; He *et al*. 2020) [44, 25]. Thus, water availability is the key requirement for rice cultivation in each of the rice ecosystems. This forces us to develop new techniques of water management for rice cultivation that specifically improve production in different ecosystems (Carracelas *et al*. 2019) [12]. Aerobic rice (AR) is one of the promising rice cultivation systems for managing water and growing rice under water-limited conditions, thus decreasing water losses by 27–51% and increasing water productivity by 32–88% (Joshi *et al*. 2009) [33]. Aerobic rice varieties are usually grown in upland conditions in unpuddled soil in non-flooded conditions, that is, unsaturated (aerobic) soil with less water requirement (Joshi and Kumar 2012) [32]. Under these conditions, the cultivation of high-yielding aerobic rice genotypes may help to save water. Other approaches that decrease water consumption are alternate wetting and drying of the field; saturated soil culture (SSC) that relies on forming farming beds, separated by furrows in which a shallow depth of water is maintained; mid-season drainage; delayed flooding; and sprinkler irrigation.

Developing the farm-level adoption of climate-resilient production systems for rice (*Oryza sativa* L.) is crucial to empower farm families to sustain their household food security. Under rice-based cropping systems, ~40% of area and ~50% of production comes from the Indo-Gangetic Plains (IGP) of India (Jat *et al*., 2020; Naresh *et al*., 2018) [28, 51]. Rice is a global primary food and is cultivated over 162 M ha, covering approximately 11% of global cultivable land that produces approximately 758 Tg (million metric tons) of rice per annum (Lal *et al*., 2020) [40]. In the Puddled transplanted rice-based production systems are high energy and cost intensive, and result in a less profitable production system (Kumar *et al*., 2021) [38]. In consequence, there is an imperative need to identify possible suitable crop establishment methods, specifically for rice production systems, to reduce the adverse impacts of climate change and increase productivity and profitability (Kumar *et al*., 2021; Zewde *et al*., 2018) [38, 71]. Direct seeded rice (DSR) systems have significant potential to reduce the environmental footprint and increase production (Kumar *et al*., 2021; Yadav *et al*., 2020) [38, 70]. Consequently, maintained productivity and sustained environmental quality could be achieved through improved production (Gathala *et al*., 2020; Nandan *et al*., 2021). Nowadays, productivity has become stable due to present crop cultivars. In India, most of the farming community use long-duration rice varieties (>140 days), which postpone the planting of succeeding winter crops. Alternative suitable winter crops are decisive and largely depend on the rice harvesting (Bhatt *et al*., 2021; Chandra *et al*., 2022) [7, 13]. Puddled transplanted rice is an energy-intensive crop establishment method for rice and is known to degrade the soil system and negatively impact succeeding winter crops (Singh *et al*., 2019; Rao *et al*., 2021) [60, 57]. To overwhelm the limitations of late seeding, alternative techniques must be adopted. DSR might be a suitable alternative to advance climate-resilient methods in an efficient manner (Sandhu *et al*., 2021) [58].

Direct seeding of rice refers to the process of establishing the crop from seeds sown in the field rather than by transplanting seedlings from the nursery (Farooq *et al*., 2009; Naresh *et al*., 2011) [17, 47]. Direct seeding avoids three basic operations, namely, puddling (a process where soil is compacted to reduce water seepage), transplanting and maintaining standing water. There are three principal methods of establishing the direct seeded rice (DSR): dry seeding (sowing dry seeds into dry soil), wet seeding (sowing pre-germinated seeds on wet puddle soils) and water seeding (seeds sown into standing water). Rice consumes around 27% of the world total fresh water withdrawal (Bouman *et al*., 2007; Naresh *et al*., 2011) [10, 47]. For wetland rice production, puddling alone requires 30% of the crop water consumption (Chauhan and Opeña, 2012) [14]. Predictions indicate that 17–22Mha of irrigated rice area in Asia will face water scarcity (Tuong and Bouman, 2002) [66] by 2025, necessitating water-saving options to be practiced widely. Manual rice transplanting requires 25–50 person-days ha^{-1} while the size of the workforce in agriculture declined by nearly 30 million between 2004–05 and 2011–12 due to rapid economic growth in Asia in non-agricultural sectors and increased labor wages (Zhang *et al*., 2011) [72].

Wetland rice production contributes almost 12% of anthropogenic methane and 55% of agriculturally-sourced greenhouse gas (GHG) emissions in the world. Solutions to all problems can be found in modifications of crop establishment practices (Chakraborty *et al*., 2017; Tyagi *et al*., 2022; Alam *et al*., 2016 Alam *et al*., 2014) [15, 68, 4, 3]. Among the crop production factors, tillage alone contributes up to 20% of crop production costs (Khurshid *et al*., 2006) and strongly influences soil properties (Alam *et al*., 2016) [4] Mechanical direct-seeding and transplanting under non-puddled/non-flooded conditions have been developed and evaluated by researchers in collaborations with farmers (Haque *et al*., 2016) [24]. In addition, rice and upland crops are grown in a sequence with repeated cycling between anaerobic and aerobic conditions (Zhou *et al*., 2014) [73]. The contrasting environments alter the soil C and N cycles, GHG emissions, soil chemical and biological properties (Zhou *et al*., 2014) [73].

The following are the major constraints associated with the productivity and sustainability of rice-based systems: (1) increasing scarcity of water and labor, (2) inefficient use of inputs (fertilizer, water, labor), (3) climate change and variability, (4) emerging energy crisis and hike in fuel prices, (5) multiplying cost of cultivation, and (6) other issues like rapid urbanization, migration of labor to cities, non-agricultural work preferences, and farm-related pollution (Ladha *et al*., 2009) [41]. Better agronomic management practices and innovations in technology are required to overcome these problems. Direct seeded rice (DSR) seems a viable option to make this shift. DSR refers to the process of sowing rice seeds directly into the field in place of transplanting the rice seedlings from the nursery. Upgraded short-duration and high yielding varieties and nutrient, weed, and resource management techniques encouraged the farmers to switch to DSR culture. This review aims to develop best-bet agronomic practices so that ecological and agronomic input efficiency can be enhanced and the environmental footprint of PTR can be reduced.

Crop Establishment

The rice crop can be planted by different methods such as dry direct seeding, wet direct seeding, and transplanting (manual and mechanical). Each planting technique differs from the other (Farooq *et al*., 2009) [17]. Puddled transplanted rice is one of the most popular techniques used among the farmers of South Asia. Different crop establishment methods in rice are being used (Figure 1). DSR options {(dry DSR by a Happy Seeder, a zero-tillage machine, a multi-crop planter, and a manual rice-wheat seeder), (wet DSR by a drum seeder), and (transplanting-mechanical transplanting by a six and eight row transplanted), and (manual transplanting by maintaining row spacing with the help of a rope)}.

Optimum plant density with uniform crop emergence is crucial for attaining good yields in DSR. Good crop establishment depends on many factors, *viz*., soil type, seedbed preparation, sowing date, seed rate and seed preparation, planting machinery used, and depth of seeding. The soil type recommended for the direct-seeded crop is medium to heavy textured soils because it suffers from iron deficiency in light soils, which can cause significant yield losses (Kaur and Singh, 2017; Tyagi *et al*., 2019) [35, 67]. The seedbed should be free of weeds and precisely leveled at sowing. To treat an herbicide such as a paraquat or glyphosate, it is necessary to knock down any existing annual or perennial weeds. Sowing time varies from location to location. In northern India, rice is grown during the Kharif season before the onset of the monsoon. The optimum time for sowing DSR is about 10–15 days before the onset of monsoon (Kamboj *et al*., 2012; Kumar and Ladha, 2011; Naresh *et al*., 2018) [34, 39, 51]. In general, seeding time for DSR should be as close as possible to the time of nursery sowing for the PTR.

Fig 1: Different crop establishment methods of rice.

Adverse climatic conditions have negatively affected agriculture production systems. The traditional puddled transplanted rice planting system is input intensive and degrades the soil system (Pandey and Velasco, 2002) [52]. Irrespective of both crop establishment methods, direct seeded rice has a superior yield (+10%) to mechanically transplanted rice. Due to intensive cultivation practices, puddling and submergence conditions during the cropping season increase environmental footprints (Farooq *et al*., 2009) [17]. The traditional puddled transplanted rice planting system is most popular among the farming community. The DSR option is cost effective and environmentally friendly compared with the puddled transplanted rice system. Currently, farmers are shifting from the traditional puddled transplanted rice system to modern rice seeding methods (dry DSR and wet DSR) (Pandey *et al*., 2002) [52]. DSR allows crop seeding in dry conditions. Traditional methods, however, require intensive tillage, puddling, and submergence (4–6 cm) conditions. The DSR method has various benefits over the traditional puddled transplanted rice planting systems (Tuong *et al*., 2000) [65]. Meanwhile, the DSR crop will have a 10–14 day advantage in maturity in comparison with the traditional planting method (Gupta *et al*., 2006) [23].

Fig 2: Agricultural practices followed in direct seeded rice cultivation systems: (A) land preparation, (B) manual seed sowing, (C) seed showing using mechanized seed drill, (D) installation of sprinkler irrigation system, (E) irrigation through sprinkler system at seedling stage, (F) field view of DSR field at seedling stage, (G) manual weed control using wheel hoe, (H) mechanized weed control using boom tractor sprayer.

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The DSR crops have higher nutrients and are water and carbon efficient (Jat *et al*., 2020; Kaur and Singh, 2017) [31, 35]. Additionally, puddled transplanted rice enhances greenhouse gas emissions. As reported by Pathak *et al*. (2013) [54] in the districts of Punjab, direct seeding decreased the total global warming potential by approximately 33%. Puddled transplanted rice crop growth and development suffered after puddling, which could lead to poor rooting due to compaction and poor aggregation in the soil system (Gathala *et al*., 2011; Naresh *et al*., 2015) [19, 18]. The DSR method is cost, energy, and input efficient compared with traditional planting methods (Gangwar *et al*., 2008) [18].

Saving water or reducing water inputs?

Reducing water inputs is not always synonymous with saving water. In areas where water is already scarce, farmers must be equipped with technologies to grow rice with less water, not to save water but simply because there is not enough water to grow rice in the conventional way. Tuong and Bouman, (2002) [66] reported that an amount of total water input into a rice field ranges from 900 to more than 3000 mm, though the transpiration demand of the crop in the tropics is in the range of 350 to 550 mm only. Water is also lost into the atmosphere via evaporation during the land preparation period (100–180 mm), via evaporation from soil or water surfaces in between rice plants (150–200 mm), and via transpiration from weeds. The outflows consist mainly of the bypass flow during land preparation (350–1500 mm) and seepage and percolation (300–1500 mm) during the crop growth period.

Bouman *et al*. (2005) [9] studied that on average, aerobic fields used 190 mm less water in land preparation, and had 250-300 mm less seepage and percolation, 80 mm less evaporation, and 25 mm less transpiration than flooded fields. Yadav *et al.* (2011) [80] revealed that the irrigation water use efficiency was higher in alternate wetting and drying (AWD) than daily irrigated treatments. It was also found that irrigation scheduling at 20 KPa soil water tension results in 33-53 per cent saving of irrigation water in dry direct-seeded rice than transplanted rice. The yield component of DSR and PTR were similar when irrigation was scheduled daily and at 20 KPa soil moisture tension.

Singh *et al*. (2005) [61] reported that after germination of direct seeded rice (DSR), irrigation can be delayed for around 7-15 days depending on soil texture. Delayed irrigation facilitates deeper rooting and makes seedlings resistant to drought. Water requirement and ponding of water requirement is very low in case of DSR, irrigation frequency of 3-7 days after the disappearance of water from the field can be practiced. Under limited water supply and drought situations, irrigation can be delayed up to 10-15 days, but care should be taken that irrigation is crucial once tillering has begun.

Jat *et al*. (2009) [29] also found reduced water input (irrigation plus rainfall) by 9-24 per cent with direct-seeded rice in comparison with puddled transplanted rice. Tabbal *et al*. (2002) [64] reported that direct-seeded rice required 19 per cent less water than puddled transplanted rice during the crop growth period and increased water use efficiency by 25-48 per cent with continuous standing water conditions.

Sudhir-Yadav *et al*. (2011) [63] found that irrigation water productivity was higher in alternate wetting drying (AWD) than in daily irrigated treatments. Due to large reductions in irrigation water amount from 40 and 70 kPa irrigation schedules, there was reduction in the grain yield. There was a large effect of both treatments on irrigation water productivity (WPI). However, WPI irrigated at 20 kPa was significantly higher than all other treatments. Input water productivity (WPI+R) was much lower than WPI in the respective treatments each year due to the large amount of rainfall each year.

In DSR, crop established after applying pre-sowing irrigation, first irrigation can be applied 7-10 days after sowing depending on the soil type. When DSR crop is established in zero tilled (ZT) conditions followed by irrigation, subsequent 1-2 irrigations are required at interval of 3-5 days during crop establishment phase. Subsequent irrigations at interval of 5-7 days need to be applied in DSR crop. During active tillering phase *i.e.* 30-45 days after sowing (DAS) and reproductive phase (panicle emergence to grain filling stage) optimum moisture (irrigation at 2-3 days interval) is required to be maintained to harvest optimum yields from DSR crop. In a 6-year study conducted in Modipuram on sandy-loam soil, it was observed that dry-DSR can be irrigated safely at the appearance of soil hairline cracks (Gathala *et al*., 2011) [19].

Drill seeding of rice and wheat on reduced-till flat land (RT-DSR/RT-DSW) or on raised beds (Bed-DSR/Bed-DSW) saved irrigation or total water use by 62 to 532 mm ha^{-1}, but was less productive than conventional practices; yield loss was high in narrow raised bed planted crops (Naresh *et al.*, 2013). (Sandhu *et al.*, 2012; Gathala *et al.*, 2013) reported that Irrigation water productivity (IWP) was significantly higher in beds to the tune of 13.9% and 13.16% than flat puddled planting. He also revealed that the rice transplanted on beds required 15.4% and 15.3% less irrigation water than that required in puddled plots. The reduction in amount of irrigation water applied in beds may be attributed to the less depth of irrigation water application to beds (5 cm) as compared to puddled plots (7.5 cm). Naresh *et al.* (2014) revealed that different crop establishment techniques, conventional-tilled puddle transplanted rice (CT-TPR) required 14%–25% more water than other techniques. Compared with the CT-TPR system, zero till direct-seeded rice (ZT-DSR) consumed 6%–10% less water with almost equal system productivity and demonstrated higher water productivity. Similarly, wide raised beds saved about 15%–24% water and grain yield decrease of about 8%.

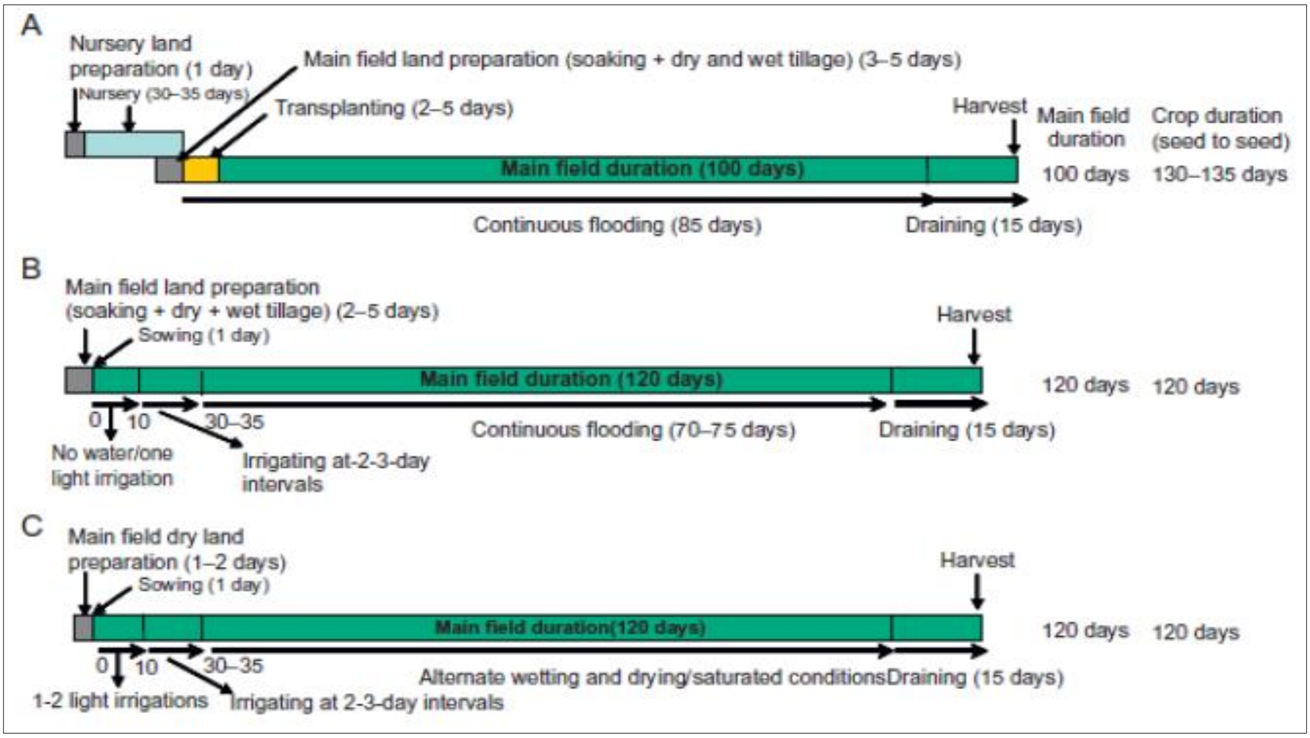

Fig 3: Various cultural activities, including irrigation schedules of puddled transplanting (A), direct wet seeding (B), and direct dry seeding (C)

Bhushan *et al*. (2007) [81] reported similar yields with much higher tiller and panicle density and lower floret fertility in direct seeded rice compared with puddle transplanted rice. However, in the second year, yield of direct seeded rice was significantly lower than of puddle transplanted rice (by 13%). Sudhir Yadav *et al*. (2011b) [63] observed that yields of both direct seeded rice and puddle transplanted rice to decline when the soil was allowed to dry to higher soil matric tensions than 20 kPa and the yield decline was more rapid in direct seeded rice than that of puddle transplanted rice as the tension increased to 40 and 70 kPa. On a marginally sodic silt loam at Modipuram, yield of direct seeded rice declined significantly to 15% as suction increased from 10 to 20 kPa at 20 cm (Sharma *et al*., 2002) [82]. De Datta *et al*. (1975) [85] reported that a water deficit during vegetative and reproductive phase reduced rice yield by 34% and 50%, respectively.

Continuous submergence consumed highest total water use (122.2 cm) produced the lowest grain yield (4.71 t ha^{-1}) resulting in to lowest water use efficiency (84.34 kg ha^{-1} cm). On the contrary, application of irrigation water to 5 cm depth when water level in PVC pipe fell to 15 cm below ground level gave the highest yield (5.69 t ha^{-1}) consequently the highest water use efficiency (85.55 kg ha^{-1} cm) with quite a large water saving (15 cm) compared to continuous submergence (Rahman and Shiekh, 2014) [56]. Water productivity of continuous submergence (0.56 kg m^{-3}) was lowest as compared to AWD - Flooding to a water depth of 5 cm when water level drops to 10 cm below ground level (0.94 kg m^{-3}) (Kishor *et al.*, 2017) [37].

Bhatt *et al*. (2014) [6] reported in a sandy loam soil that grain yields of wet-direct seeded rice was significantly better over direct seeded rice sown in conventionally tilled plots, direct seeded rice sown in zero tilled plots, mechanically transplanted rice in zero tilled plots while at with mechanically transplanted rice in puddle plots and puddled transplanted rice because of better tillers, 1000 grain wt and highest panicle fertility while conventionally tilled and zero tilled counterpart treatments suffering from the problem of heavy weed pressure, iron deficiency. It was worth to mention here that seed drill and drum seeder meant for direct seeding of rice sow rice seeds at a spacing of 20 cm, mechanical transplanter transplant mat type rice seedlings at a row to row 30 cm with plant to plant 17 cm spacing while in puddle transplanting was done at a row to row 20 cm and plant to plant spacing of 15 cm. However, coming to the water productivity, mechanically transplanted puddle rice plots comes up even above the wet-direct seeded rice because direct seeded rice crop appeared almost a month advance than mechanical transplanted and puddles transplanted rice crop plots and thus received higher number of irrigations, hence even reporting highest grain yields, the performance in terms of water productivity in direct seeded rice treatment found to be lower than mechanical transplanted and puddle transplanted treatments.

Gupta *et al*. (2003) [22] reported the 20% decrement in irrigation amount. They further reported that direct seeded rice on raised beds decreased water use by 12–60%, and increased yield by 10% as compared to puddle transplanted rice, in trials at both experimental stations and on-farm. Further, Gill *et al*. 2006 reported that water productivity in direct seeded rice was 0.35 and 0.76 as compared to 0.31 and 0.57 under puddle transplanted rice during 2002 and 2003, respectively, indicating better water-use efficiency. Avoiding water stress and keeping the soil wet in direct seeded rice experiments at the following stages: tillering, panicle initiation, and grain filling (Gopal *et al*., 2010) [21].

Trade of Puddling on GHG and Climate Change Mitigation

The continuous submergence of soil under flooded rice promotes the production of methane, an important greenhouse gas. Temporary or complete soil aeration, such as in AWD or aerobic rice, respectively, can reduce methane emission. Soil aeration, on the other hand, can increase the emission of nitrous oxide, another greenhouse gas. The direct seeding of rice in dry soil (DSR) decreased CH_4 emission as DSR fields were not continuously submerged with water (Pathak *et al*., 2013) [54] but the DSR increased N_2O emission due to the aerobic conditions. The overall net effect of DSR would be to decrease the GWP by a quarter (16–33%) if the entire area of the IGP under CT could be converted to DSR for the rice-based cropping system (Pathak *et al*., 2013) [54]. Conventional tillage followed by dry DSR has the potential to drastically reduce CH_4 emissions by up to 60%, though it is known to create conditions for the emission of N_2O (Ishibashi et a., 2007) [27]. Chakraborty *et al*. (2017) [15] in a global data meta-analysis found that CH_4 emissions were also significantly lower in conventional tillage DSR under wet and dry conditions, and ZT DSR under wet condition. The largest CH_4 emission reduction (63%) was recorded in ZT DSR under dry condition while the reduction in CT DSR under dry condition was 44%. In CT DSR, CH_4 emission was 60% less than in conventional puddled transplanting of rice under wet condition. The N_2O emissions was increased by 34% in CT DSR while under non-puddled transplanting under wet condition and ZT DSR under dry condition, N_2O emissions remained unchanged. Aulakh *et al*. (2001) [5] reported N_2O production during rice growing season is 15–450 gN_2O–N ha^{-1} d^{-1} and in a well-drained sandy loam soil ranging from 15–60 g N_2O–N ha^{-1} d^{-1} during pre-rice fallow period. In Northwest India, N_2O release rates during post-rice fallow and wheat crop were 20–43 and 5–33 g N_2O–N ha^{-1} d^{-1} respectively, resulting in seasonal flux of 2.6–3.4 kg N_2O–N ha^{-1} (Aulakh *et al*. (2001) [5].

Puddling of rice soil followed by flooding resulted in emission of around 2.6 t $C0_2$–eq ha^{-1} from soils within the first few weeks. Methane (CH_4) and nitrous oxide (N_2O) are the principal GHGs emitting from rice fields. The reduced soil layer in puddled soils with very low redox potential induced CH_4 synthesis and emission Bodelier, (2003) [8] while the oxidized layer present at the interface of soil and water causes the emission of N_2O (Ponnamperuma, 1977) [55]. The availability of C substrates accelerates the survival of methanogens and the low redox potential are both driving factors for CH_4 emission (Wang and Hsieh, 2002) [69]. Liu *et al*. (2014) [42] recorded 54% higher seasonal methane emissions from conventional puddled transplanted rice fields than DSR rice, though N_2O emissions were reduced by around 49% with puddled transplanted with N application. Chakraborty *et al*. (2017) [15] in a global data meta-analysis found that higher CH_4 emissions under conventional puddled transplanting of rice compared to novel crop establishment practices while N_2O emissions were unchanged. The reduced percolation by soil puddled layer under puddled transplanting of rice can increase methanogenesis by reducing the flow of oxygen-containing water (Sharma and De Datta, 1986) [59] and hence emissions of CH_4 to the atmosphere. Since N_2O production from both nitrification and denitrification processes is sensitive to oxygen concentration, there are reasons to suspect that flooding (anaerobic condition) and draining (Aerobic condition) of a soil will influence the N_2O emissions. The rate of N_2O emission from flooded paddy fields had been thought to be small (Minami and Fukushi, 1984) [45]. However; denitrification can produce N_2O from $N0_3$ during drainage and/or during even drier soil conditions in anaerobic microsites (Majumder, 2003) [43]. The potential for high N_2O flux is greater in wetland soils with high levels of NO_3^- and NO_2^-.

Conclusions

The crop establishment practices which outperform or match the existing rice establishment practices in terms of yield and labor requirements and do not require much technical adjustment are most readily adopted by farmers. Direct seeding saves irrigation water but grain yield was affected differently depending upon the timings as well as pattern of rainfall, water and crop management and soil type. A strategy of saving water at the field level simply to improve water productivity potentially threatens overall rice production. More rice with less water can only be achieved at the field level when water management is integrated with other crop and resource management practices to increase yield. Since technologies to reduce water inputs may have many negative impacts on labour and land productivity, they are not attractive to farmers unless suitable policies, an effective institutional organization are available to promote their adoption. Under mild water-short conditions, the emerging aerobic rice system can potentially produce more rice with less water than flooded rice systems. 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. Reduces irrigation water loss through percolation due to fewer soil cracks. Moreover, water productivity is high in DSR and exceeds corresponding values in transplanting by >25%. The promising approaches are to improve water management to bridge the yield gap, by use of advanced strategies and technologies that are developed location specific.

To produce more rice, field-level technologies have to be integrated with system-level management and technologies such that the water saved at the field level is used more effectively to irrigate previously un-irrigated or low-productivity lands. In many rice areas where there is already a high degree of recycling and conjunctive use of water, technologies to reduce outflows from the field may conflict with existing system-level technologies, and the amount of water that can be saved in the system could be far less than assumed from computations of field-level water savings. The impact of reducing water inputs for rice production on sustainability and environmental services of rice ecosystems warrants further investigation. The success of direct seeded rice is location specific and site specific apart from depending on the rainfall and weather conditions and dependent on effective weed management programme, timely irrigations and foliar sprays of micro-nutrients so that declining soil fertility, underground water levels and livelihood of the poor farmers could be improved in the region.

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