International Journal of Research in BioSciences
Vol. 2 Issue 2, pp. (1-12), April 2013
Available online at http://www.ijrbs.in
ISSN 2319-2844

Review Paper

Different rice establishment methods for producing more rice per drop of water: A review

***Lal B.[1], Gautam Priyanka[1] and Joshi Ekta[2]**
[1]Crop Production Division, Central Rice Research Institute, Cuttack, Odisha, INDIA
[2]Division of Agronomy, Indian Agricultural Research Institute, New Delhi, INDIA

(Received January 05, 2013, Accepted March 28, 2013)

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. Water shortage is becoming severe in many rice-growing areas in the world, prompting the introduction of water-saving aerobic rice, which is direct-seeded in non-puddled, nonflooded aerobic soil, aerobic rice systems can reduce water use in rice production by as much as 50% 'Aerobic rice' and 'upland rice' are both grown under aerobic conditions. However, the former is under controlled water management, but the latter is not. Although the technology of growing rice with the new AWD and aerobic rice systems need to be further refined or developed, a broad adoption of these systems is expected to ensure rice production in water short areas, and result in significant water saving. This paper introduces principles that govern technologies and systems for reducing water inputs and increasing water productivity. 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.

Keywords: Aerobic rice, AWD, Water productivity, etc.

Introduction

Food security depends on the ability to increase production with decreasing availability of water to grow crops. Rice, as a submerged crop, is a prime target for water conservation because it is the most widely grown of all crops under irrigation. To produce 1 kg of grain, farmers have to supply 2–3 times more water in rice fields than other cereals [1]. In Asia, more than 80% of the developed freshwater resources are used for irrigation purposes; about half of which is used for rice production [2]. Rapidly depleting water resources threaten the sustainability of the irrigated rice and hence the food security and livelihood of rice producers and consumers [3]. In Asia, 17 million hectare (Mha) of irrigated rice areas may experience ''physical water scarcity'' and 22 Mha may have ''economic water scarcity'' by 2025 [4]. There is also much evidence that water scarcity already prevails in rice-growing areas, where rice farmers need technologies to cope with water shortage and ways must be sought to grow rice with lesser amount of available water [4].

Rice is very sensitive to water stress and attempts to reduce water inputs may tax true yield potential. The challenge is to develop novel technologies and production systems that would allow rice production to be maintained or increased at the face of declining water availability. Several strategies are in vogue to reduce rice water requirements, such as saturated soil culture [5], alternate wetting and drying (AWD) [6], ground-cover systems [7], system of rice intensification (SRI) [8], aerobic rice [9], raised beds [10], etc. Development of rice varieties through conventional breeding, marker-assisted selection (MAS), and employing biotechnological tools for water-limited conditions are the areas of current research [11].This paper discusses strategies and options to make rice production more water-efficient with integrative use of crop improvement and management tools.

Aerobic rice system to improve water productivity

Aerobic rice is a new way of production system in which specially developed, input-response rice varieties with aerobic adaptation are grown in well-drained, non-puddled, and non-saturated soils without ponded water [7]. It entails growing rice in aerobic soil, with the use of external inputs such as supplementary irrigation and fertilizers, and aiming at high yields [12].Main driving force behind aerobic rice is the economic water use. A fundamental approach to reduce water inputs in rice is growing like an irrigated upland crop, such as wheat or maize. Instead of trying to reduce water input in lowland paddy fields, the concept of having the field flooded or saturated is abandoned altogether [12].

The adoption of aerobic rice is facilitated by the availability of weed management tools and seed-coating technologies. Case studies showed yields to vary from 4.5 to 6.5 t ha^{-1}, which is about double than that of traditional upland varieties and about 20–30% lower than that of lowland varieties grown under flooded conditions. However, the water use was about 60% less than that of lowland rice, total water productivity 1.6–1.9 times higher, and net returns to water use was twofold higher. Aerobic rice requires lesser labor than lowland rice and can be highly mechanized [13]. Input water savings of 35–57% have been reported for dry seeded rice (DSR) sown into nonpuddled soil with the soil kept near saturation or field capacity compared with continuously flooded (5 cm) transplanted rice [10].However, yields were reduced by similar amounts due to iron or zinc deficiency and increased incidence of nematodes. Contrary to the results of small plot replicated experiments, participatory trials in farmers' fields in India and Pakistan suggest a small increase or 10% decline in yield of DSR on the flat compared with puddled transplanted rice, and around 20% reduction in irrigation time or water use [14].

A high-yielding lowland rice variety (IR20) like an upland crop under furrow irrigation, [15] reported that total water savings were 56% and irrigation water savings 78% compared with growing the crop under flooded conditions. However, the yield was reduced from 7.9 to 3.4 t ha^{-1}. The WUE of the aerobic varieties under aerobic conditions was 164–188% higher than that of a lowland cultivated rice variety. Aerobic rice maximizes water use in terms of yield and is a suitable crop for water-limiting conditions [16]. In a study, rice yields under aerobic conditions were 2.4–4.4 t ha^{-1}, which were 14–40% lower than under flooded conditions [17]. However, water use decreased relatively more than yield, and water productivity under aerobic cultivation increased by 20–40% (in one case even 80%) over that under flooded conditions. The aerobic rice technology eliminates puddling and flooding, and presents an alternative system in reducing water use and increase water productivity. Aerobic rice saved 73% of irrigation water for land preparation and 56% during the crop growth period [17]. In a two year field experiment at Indo-Gangetic plains to evaluate various tillage and crop establishment systems for their efficiency in labor, water and energy use, and economic profitability, the yields of rice in the conventional puddled transplanting and direct-seeding on puddled or non-puddled (no-tillage) flat bed systems were equal [18]. Nevertheless, decline in yield was observed when aerobic rice was continuously grown and the decline was greater in the dry than in the wet season [19]. In crux, aerobic rice is an attractive option to the traditional rice production system. Yield penalty and yield stability of aerobic rice have to be considered before promoting this water-saving technology.

Direct seeded rice and water use efficiency

New water cannot be created; thus, we have to conserve and make judicious use of every drop. Two possible options are to minimize water losses through better management thus ensuring more water for crop production, and improve water use efficiency, i.e. increase in production per unit of water. Soil type influences the need for irrigation water, e.g. coarse-textured soils have higher percolation losses. Land leveling also facilitates uniform water application in less time and helps in weed control. There are few reports evaluating mulching for rice, apart from those from China, where 20–90% input water savings and weed suppression occurred with plastic and straw mulches in combination with DSR compared with continuously flooded TPR [7].Extensive research is needed to improve water productivity and WUE in DSR systems.

Alternate wetting and drying irrigation method and water productivity

AWD has been commonly used as a water-saving practice in many parts of the world for more than a decade [20]. In this system, the soil is allowed to dry for a few days within irrigation events depending on plant developmental stages [20,21]. Some success has been reported as far as yield and water demand is concerned [22] however, unproductive water losses could not be totally avoided by AWD. Hence, the water consumption is still high in AWD since the soils need to be submerged at least during the irrigation period. Savings in irrigation water in the AWD treatments were 53–87 mm (13–16%) compared with the continuously submerged regime. Rice grain yields ranged from 7.2 to 8.7 t ha^{-1} and were not markedly affected by the water regimes. Water productivity was significantly higher in the AWD regime than in the continuously submerged regime [23].

Yield penalty was commonly observed under AWD compared with continuously flood-irrigated (CF) rice [12]. In general, AWD increased water productivity with respect to total water input because the yield reduction was smaller than the amount of water saved. Variety has a large influence on the grain yield of AWD [19]. Six out of 30 different varieties demonstrated higher yields in AWD than CF [15]. The development of water-saving and drought-resistance rice (WDR) is another strategy to produce more rice with less water [24]. WDR aims to produce the same yield as paddy rice with much less water consumption (50% water saving compared with the normal paddy rice) under irrigated conditions. At the same time, WDR should have the ability of drought tolerance to minimize yield loss under water-limited conditions. Several field studies were conducted to determine grain yield, water saving, water productivity and drought tolerance of HY3. HY3 demonstrated an ability of drought tolerance. Water saving and relatively high yield was also achieved in HY3. However, these studies did not compare HY3 with high-yielding varieties for the continuously flood-irrigated rice system such as “super” hybrid rice varieties. China’s “super” hybrid varieties have increased rice yield potential by 8–15% compared with ordinary hybrid and inbred varieties. Increased sink size due to large and heavy panicles and improved biomass production due to great canopy light interception are responsible for high yield potential of “super” hybrid rice [25]. Up to now, about 70 “super” hybrid rice varieties were commercially released in China [26].In recent years, “super” hybrid rice varieties have occupied about 20% rice planting areas in China. However, the high-yielding of “super” hybrid rice varieties was often achieved when water was amply supplied. It is unknown if these varieties that were developed for the continuously flood-irrigated rice system are suitable for AWD conditions.

System of rice intensification for higher productivity

SRI that evolved in the 1980s and 1990s in Madagascar permits resource limited farmers to realize paddy yields of up to 15 t ha^{-1} even on infertile soils, with greatly reduced rates of irrigation and without external additional inputs[8]. The main features of this system are transplanting young seedlings singly in a square pattern with wide spacing, using organic fertilizers and hand weeding, and keeping the paddy soil moist during the vegetative growth phase. Significant phenotypic changes occur in plant structure and function and in yield and yield components under SRI cultivation. SRI increased yields substantially (50–100% or more), while requiring only about half as much water as conventional [27], whilst not needing the purchase of additional external inputs.

SRI is difficult for most farmers to practice because it requires significant additional labor inputs at a time of the year when liquidity to hire labor is low and family labor effort is already high. This poses the challenge to researchers and policymakers concerned with the promotion of water saving rice technologies. Even though the yields can be increased while saving water, adoption by farmers is still far from assured. SRI methods are able to enhance yields of any rice variety, but the highest yields have come from improved high-yielding varieties. Factorial trials in Madagascar explain synergistic dynamics among the SRI practices that account for 100–200% increases in yield [27].A large increase in the productivity of irrigation water use with SRI can make water savings more attractive, compensating farmers well for the extra labor or expenditures involved. The returns to land, labor, capital, and water are all increased by the use of SRI practices [28].

Lu et al. 2000 [22] evaluated some modifications in traditional SRI, viz. transplanting three separated seedlings in one hill in a triangular pattern with the leaf age extended to 3–4 weeks; application of herbicide before transplanting; mulching the spaces between plants with straw; adding chemical fertilizers to promote plant growth vigorously when needed; making shallow furrows before transplanting in the zero-till fields; and applying the AWD method for water management with midseason drainage to inhibit tillering. With these modifications, grain yield exceeded 12 t ha^{-1}, being 46% greater than in control using field comparison along with water saving. Moser and Barett, 2003 [29] conducted a survey of farmers in Madagascar to investigate farmer implementation of AWD as part of SRI and showed that farmers have adapted AWD practices to fit the soil type, availability of water and labor. The primary drawbacks reported by farmers with implementing AWD were the lack of a reliable water source, little water control, and water-use conflicts. They suggested that by combining AWD with SRI, farmers can increase grain yields while reducing irrigation water demand [29]. Uphoff et al.2008 [28] proposed that continuously flooded soils constrain root growth and contribute to root degeneration. Moreover, soil microbial life is limited to anaerobic populations. This excludes contributions to plant performance from mycorrhizal fungal associations that are of benefit to most plant species. Keeping paddy fields flooded also restricts biological nitrogen fixation to anaerobic processes, forgoing possibilities for aerobic contributions.

In another study, Thiyagarajan et al. 2003 [30] reported savings in irrigation water of 56% and 50% using conventional and young seedlings, respectively, without a significant effect on grain yield under SRI system. Two week- old seedlings planted one seedling per hill produced significantly higher yield (6.43 t ha^{-1}) than the farmer's practice of using 21-day-old seedlings (5.96 t ha^{-1}). However, yields were similar for both age groups when the number of seedlings increased to 2 and 4 per hill. The performance of 15-day-old seedlings improved more than that of 21-day-old seedlings with the addition of well-decomposed organic matter and intermittent irrigation.

In a cement-box experiment in China, production characteristics, water-use efficiency, nitrogen-use efficiency, and major physiological characteristics of three alternative water management practices SRI, GCRPS, and AWD were compared with a conventional flooded rice system. Water supply in SRI and AWD was 46% and 36% lower than in conventional flooded rice system, respectively; whereas their yields were similar or significantly higher (5% for SRI and 8% for AWD), resulting in greater WUE. The higher yields of SRI and AWD compared with conventional flooded rice system were associated with higher harvest indices but not with differences in total biomass production. Water supply and yield in GCRPS were 65% and 62% lower than in conventional flooded rice system [31].

SRI and water productivity

SRI has attracted the most attention. SRI techniques include line transplanting of single young seedlings at wide spacing, mechanical weed control, AWD irrigation, and the application of organic soil fertility amendments, preferably compost or manure. SRI's advocates argue these techniques provide very high yields and improve water productivity [27]. SRI is now supported by institutions ranging from farmers' organizations to NGOs and the World Bank, and is promoted in 47 countries globally [32], though its popularity has not come without controversy.

Krupnika et al. 2012 [33] explain that substantial water savings and increases in water productivity can be obtained with SRI, although significant yield increases compared to RMP should not be expected. Positive effects resulting from straw incorporation followed by fertilizer application became apparent in the fourth season as significant additive increases in yield; straw and fertilizer N recovery were observed under both RMP and SRI. Further work should be conducted to investigate the mechanisms underlying these results, and to compare SRI's yield and water productivity performance to other water-saving rice management systems. If farmers in the Sahel practicing double cropping choose to experiment with techniques like SRI to reduce water use and thus input costs, our findings indicate that they are most likely to benefit over time by practicing straw residue incorporation followed by mineral fertilizer additions, although when nutrient additions are held equal, SRI is unlikely to improve yield trends over long-established Recommended Management Practices.

Effect of ground-cover rice production system on water saving and grain yield

The plastic film or straw mulching rice production systems have been developed since 1990 in China to improve the tolerance to low temperatures [34]. This is similar to the success in Japan in the 1960s, but now its benefits for water-saving rice production led to the adoption of this system. In plastic film mulching (PFM), also called GCRPS, lowland rice varieties are used and the soil is kept humid by covering materials [35]. In GCRPS, soil is irrigated to approximately 80% of water-holding capacity. Nevertheless, the amount of water saved with this system can be as high as 60–85% of the need in the traditional paddy systems with no adverse effects on grain yield [36].However, some researcher reported significant yield reductions under such conditions [37]. Thereafter, to check evaporation the soil surface is covered by material, such as plastic film, paper, or plant mulch [7].

Although benefits of water-saving rice cultivation in water-limited areas have been illustrated, other experimental evidences suggest moderate to severe yield reduction [37] of water-saving cultivation compared to paddy. With lower soil water potentials the elongation of internodes, the number of panicles and the crop growth rate reduced in comparison to flooded conditions [22]. Lin et al. 2003 [7] recorded up to 60% reduction in water requirements of rice crop in a GCRPS; however, grain yields were up to 10% lower than the traditional lowland rice. This was associated to micronutrient deficiency and difficulties in nitrogen fertilizer management contributed to higher yield penalty in GCRPS.

Raised beds system for water saving in rice

Currently, puddling induces high bulk density, high soil strength and low permeability in subsurface layers [38]. These factors restrict root development, water and nutrient use from the soil profile by wheat sown after rice. The development of hardpan also leads to aeration stress in wheat crop at the time of the first irrigation and this problem is predominant in the region where rice–wheat system is being practiced. Thus, puddling in rice results in reduced grain yield of succeeding wheat crop [38]. Various technologies for water saving in rice like direct seeding, ground cover system, alternate wetting and drying, direct seeding and transplanting on beds (soil saturation culture), etc. are being tested. The latter one, i.e. transplanting of rice on beds omits puddling and hence avoids the detrimental effects of puddling. In this case rice is grown on raised beds and irrigation is applied in furrows between the beds. Although, numerous studies suggest water saving associated with plant installation in beds, water management (continuously flooded condition or intermittent irrigation) is often poorly reported. This is an important consideration in assessing whether the raised beds saved irrigation water because of their particular geometry or whether the water saving was the result of applied intermittent irrigations which can also be applied to flat land [38]. Transplanting of rice seedlings on slopes of freshly constructed beds resulted in 15% saving of irrigation water as compared to puddled plots (conventional method used by farmers) without any significant reduction in grain yield of rice. Irrigation water can also be saved in puddled transplanted rice by applying irrigation three days after disappearance of ponded water as compared to recommended practice of applying irrigation two days after disappearance of ponded water and this practice does not leads to any significant reduction in grain yield. However, beds are to be irrigated two days after disappearance of ponded water [39].

The use of raised beds for the production of irrigated non-rice crops was pioneered in the heavy clay soils of the rice-growing region in Australia in the late 1970s [40], and for irrigated wheat in the rice–wheat system of the Indo-Gangetic plains during the 1990s, inspired by the success of beds for wheat–maize systems in Mexico [41]. Potential agronomic advantages of beds include improved soil structure due to reduced compaction through controlled trafficking, and reduced water logging and timely machinery operations due to better surface drainage. Beds also provide the opportunity for mechanical weed control and improved fertilizer placement. While the potential benefits of beds for wheat production in the Indo-Gangetic plains have been known for some time, evaluation of beds for rice and permanent beds in rice–wheat system systems commenced more recently.

Farmer and researcher trials in the Indo-Gangetic plains suggest irrigation water savings of 12–60% for direct-seeded and transplanted rice on beds, with similar or lower yields for transplanted compared with puddled flooded transplanted rice, and usually slightly lower yields with direct seeded rice. However, many studies in the northwest Indo- Gangetic plains indicate little effect of rice on beds on water productivity (typically around 0.30–0.35 g kg^{-1}) as the decline in water input was accompanied by a similar decline in yield [42].The causes of reduced rice yield included increased weeds and nematodes, suboptimal sowing depth due to lack of precision, and micronutrient (e.g., iron, zinc) deficiencies.

Singh et al. [42] evaluated the yield and water use of rice established by transplanting, wet and dry seeding with subsequent aerobic soil conditions on flatland and on raised beds. Transplanted rice yielded 5.5 t ha^{-1} and used 360 mm of water for wetland preparation and 1608 mm during crop growth. Compared with transplanted rice, dry-seeded rice on flatland and on raised beds reduced total water input during crop growth by 35–42% when the soil was kept near saturation and by 47% and 51% when the soil dried out to 20 and 40 kPa moisture tension in the root zone, respectively.

Most of the water savings were caused by reduced percolation losses. Moreover, no irrigation water was used during land preparation. However, the dry seeding of rice reduced yield by 23–41% on flatland and by 41–54% on raised beds compared with transplanted rice. There was no great difference in water productivity among treatments. There appears to be little scope for saving irrigation water with furrow-irrigated rice on beds on the heavy clay soils of southern Australia. Investigations over four growing seasons showed irrigation water savings of around 10% with saturated soil culture (water continuously in the furrows), with a similar reduction in the grain yield [43].

Irrigation water use of rice grown on beds with intermittent irrigation until 2 weeks before panicle initiation, followed by continuous flooding, was similar to water use of dry-seeded rice on the flat surface with continuous flooding commencing about 1 month after sowing [44].This is in contrast with findings on a more permeable soil in semitropical southern Queensland where irrigation water use of rice on beds with saturated soil culture was 32% less than flooded rice on the flat due to considerably reduced percolation losses [37]. Studies in the USA have also shown considerable water savings with furrow-irrigated rice on beds [45]. Beecher et al. 2006 [44] reported no water saving from the raised bed rice cultivation compared with conventional ponded rice grown on a flat layout. When grown on raised beds, a variety needs to be able to compensate for the loss in cropped area (caused by the relatively large row spacing between the beds) by producing more productive tillers.

Management of cracked soils for water saving during land preparation

Tuong et al. 1996 [46] reported that bypass flow accounted for 41±57%(equivalent to about 100 mm of water) of the total water applied in the field during land soaking. Water loss throughout the period of land preparation may be much greater than this, because cracks may not close after rewetting [46], and bypass flow may continue until soil is repuddled. This might explain the very high percolation losses during land preparation, accounting for up to 40% of the total water supplied for growing a rice crop. Reducing these losses will contribute greatly to improving water-use efficiency of rice.

Straw mulching helped conserve moisture in the soil profile reduced crack development during the fallow period but did not reduce the bypass loss during land preparation. Shallow tillage formed small soil aggregates, which blocked and impeded water flow in the cracks and reduced the amount of water that recharged the groundwater via the bottom of the cracks and crack faces. Water was, therefore, retained better in the topsoil. Shallow surface tillage could reduce about 31±34% of the water input for land preparation, equivalent to a saving of 108±117 mm of water depth and shortened time required for land preparation. Water savings during land preparation may increase the service area of an irrigation system. In rainfed areas, shallow surface tillage may also lead to earlier crop establishment and, thus, reduce the risk of late-season drought. This kind of tillage does not necessarily require high-powered tractors. Furthermore, tractors/rototillers are becoming more accessible to small farmers for custom hiring, offering better opportunities for incorporating shallow surface tillage practice in the rice production system [20].

Table 1: Grain yield of rice under different crop establishment methods and irrigation treatments

Source	Treatment	Yield (t ha^{-1})
Belder et al. 2004 [56]	Flooded	8.4
	AWD	8.0
C.S. Bueno et al. 2010 [57]	Flooded	8.59
	AWD	8.21
Yao et al. 2012 [58]	Flooded	7.31
	AWD	7.26
Bouman et al. 2005 [59]	Flooded	5.06
	Aerobic	4.36
Latif et al. 2009 [60]	SRI	6.37
	BMP	6.15
	Farmers practice	4.94
Bhusan et al. 2007 [55]	DSR	7.20
	TPR	6.60

Other management practices

Soil type has a large influence on irrigation water requirement due to much higher percolation losses on coarser textured soils. This is particularly true for rice grown under submerged condition for most of the season. Seasonal percolation losses of 57–83% of the total input water are common in the Indo-Gangetic plains, with highest losses (up to 1500 mm) on sandy and sandy-loam soils, and lowest losses on loams and clay-loams (up to 890 mm) [47]. The extent of laser leveling in South Asia and China is currently extremely small, compared with 50–80% of the rice land in Australian rice-based systems [48]. Land leveling can reduce evaporation and percolation losses by enabling faster irrigation times and by eliminating depressions. It also reduces the depth of water required to cover the highest parts of the field and for ponding for weed control in rice, and therefore percolation losses, more so on more permeable soils. Rice yields in rainfed lowland laser-leveled fields were 24% higher than in without laser-leveled fields in Cambodia, and yield increased with the uniformity of leveling.

Pressurized irrigation systems (sprinkler, surface, and subsurface drip) have the potential to increase irrigation water use efficiency by providing water to match crop requirements, reducing runoff and deep drainage losses, and generally keeping the soil drier, reducing soil evaporation and increasing the capacity to capture rainfall [49]. There are few reports of the evaluation of these technologies in rice–wheat systems. In Australia sprinkler irrigation of rice to replace evaporative loss reduced irrigation water use by 30–70% [50]. Even at frequencies of up to three times per week yield declined by 35–70%. Irrigation water use was reduced by about 200 mm in rice with subsurface drip commencing 2 weeks prior to panicle initiation compared with flooded rice culture. Yields with drip also decreased, although there was no increase in irrigation water productivity [44]. Reducing non-beneficial evaporation direct from the soil or free water lying on the field is true water saving, although it may be countered to some degree by increased transpiration rates as a result of impacts on the microclimate experienced by the plant. The size of this effect has not been established. Evaporation from the free water surface accounted for 40% of the total evaporative loss from continuously flooded water-seeded rice [51].

Substantial irrigation water savings (25–30%) can be achieved by delaying transplantation from mid-May to mid-June [52]. Direct seeding could help overcome the problem of labor availability, although the optimum sowing date may need to be earlier than the optimum transplanting date, which could increase the crop water requirement. It is not clear if changing to direct seeding will increase or reduce the water requirement for rice, and the impact may vary depending on sites and systems [2]. Although delayed rice planting can save water, it can also delay planting of wheat beyond the optimal time, causing yield loss of 1–1.5% per day due to higher temperatures at grain filling [53]. While delaying transplanting in the Indo-

Gangetic plains to the optimum time saves water, bringing forward transplanting in Eastern India enabled more profitable use of rainfall. Here, irrigation water is scarce, and the need for irrigation can be avoided and total system productivity increased by establishing rice with rainfall supplemented by irrigation from groundwater during the pre-monsoon period, and by raising bund height to 20 cm to capture rainfall. There are few reports of evaluation of mulching for rice, apart from those from China, where considerable input water savings of 20–90% occurred with plastic and straw mulches in combination with aerobic culture compared with continuously flooded transplanted rice [54]. Much of the water savings was probably due to higher percolation losses in the flooded systems [7].

Future thrust

A successful change from the traditional flooded to aerobic rice production requires the breeding of special aerobic rice varieties and the development of appropriate water and crop management practices. Although, considerable progress has been made in the improvement of transgenic rice for improved water-use efficiency and productivity; however, the achievements are not satisfactory. Nevertheless, with the study of the functional genomics of plants, considerably more information about the mechanisms by which plants perceive and transducer these stress signals to initiate adaptive responses will be obtained, and with the improvement of the transgenic approach, marker-free transgenic rice will be produced. Therefore, to combine novel regulatory systems for the targeted expression with useful genes, more effective and rational engineering strategies must be provided for the improvement of rice for higher water productivity. Different strategies need to be tested experimentally to genetically improve the water-use efficiency and drought stress tolerance in rice. Different strategies need to be integrated, and the genes representing distinctive approaches be combined to substantially increase rice water productivity. Wide hybridization using hardy wild rice species is another area to be emphasized. Moreover, combining the transgenic with traditional breeding methods may be an effective approach to develop abiotic stress-tolerant rice cultivar.

References

1. Barker R et al. The outlook for water resources in the year 2020: Challenges for research on water management in rice production. In ‘‘Assessment and Orientation Towards the 21st Century’’, pp. 96–109. Proceedings of 19th Session of the International Rice Commission, Cairo, Egypt, 7–9 September 1998. FAO **(1998)**.

2. Dawe D. et al. Water supply and research for food security in Asia. In ‘‘Proceedings of the Workshop on Increasing Water Productivity and Efficiency in Rice-Based Systems,’’ July 1998, International Rice Research Institute, Los Banos, Philippines. **(1998).**

3. Tuong et al. Increasing water productivity and weed suppression of wet-seeded rice: Effect of water management and rice genotypes. J. Exp. Agric. 36, 1–19, **(2000)**.

4. Tuong T. P. and Bouman B. A. M. Rice production in water-scarce environments. Paper Presented at the Water Productivity Workshop, 12–14 November 2001. Colombo, Sri Lanka. **(2002)**.

5. Borrell et al Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. Field Crops Res. 52, 231–248, **(1997)**.

6. Tabbal et al. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agric. Water Manage. 56, 93–112, **(2002)**.

7. Lin et al. saving water with the ground cover rice production system in China. In ‘‘Technological and Institutional Innovations for Sustainable Rural Development.’’ Conference on International Agricultural Research for Development. Deutscher Tropentag, 8–10 October 2003, Gottingen. **(2003)**

8. Stoop et al. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: Opportunities for improving farming systems for resource-poor farmers. Agric. Syst. 71, 249–274, **(2002)**.

9. Bouman, et al. "Water Management in Irrigated Rice—Coping with Water Scarcity." International Rice Research Institute, Los Banos, Philippines. **(2007).**

10. Singh et al. Effects of rice establishment methods on crop performance, water use, and mineral nitrogen. In "Water-Wise Rice Production" (B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong, and J. K. Ladha, Eds.). pp. 223–235. Proceedings of a Thematic Workshop on Water Wise Rice Production, 8–11 April 2002 at IRRI Headquarters in Los Banos, Philippines. **(2003)**.

11. Cattivelli et al. Drought tolerance improvement in crop plants: An integrative view from breeding to genomics. Field Crops Res. 105, 1–14, **(2008)**.

12. Bouman B.A.M. and Tuong T.P. Field water management to save water and increase its productivity in irrigated rice. Agricultural Water Management 49(1), 11–30, **(2001).**

13. Huaqi et al Aerobic rice in northern China: Opportunities and challenges. In "Water-Wise Rice Production" (B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong, and J. K. Ladha, Eds.). pp. 207–222. Proceedings of a Thematic Workshop on Water-Wise Rice Production, 8–11 April 2002 at IRRI Headquarters in Los Banos, Philippines. **(2003).**

14. Gupta et al. Adopting conservation agriculture in the rice–wheat system of the Indo-Gangetic Plains: New opportunities for saving water. In "Water-Wise Rice Production" (B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong, and J. K. Ladha, Eds.). pp. 207–222. Proceedings of a Thematic Workshop on Water-Wise Rice Production, 8–11 April 2002 at IRRI Headquarters in Los Banos, Philippines. **(2003).**

15. De Datta et al. Water management in flooded rice. In "Water Management in Philippine Irrigation Systems: Research and Operations", pp. 1–18. International Rice Research Institute, Los Banos, Philippines. **(1973).**

16. Xiaoguang et al. Yield of aerobic rice (Han Dao) under different water regimes in North China. In "Water-Wise Rice Production" (B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong, and J. K. Ladha, Eds.). Proceedings of a Thematic Workshop on Water-Wise Rice Production, 8–11 April 2002 at IRRI Headquarters in Los Banos, Philippines. **(2003).**

17. Castaneda et al. The potential of aerobic rice to reduce water use in water-scarce irrigated lowlands in the tropics. In "Water-Wise Rice Production" (B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong, and J. K. Ladha, Eds.). Proceedings of a Thematic Workshop on Water-Wise Rice Production, 8–11 April 2002 at IRRI Headquarters in Los Banos, Philippines. **(2003)**.

18. Bhushana et al. Saving of water and labor in a rice–wheat system with no-tillage and direct seeding technologies. Agron. J. 99, 1288–1296, **(2007)**.

19. Peng et al. Comparison between aerobic and flooded rice in the tropics: Agronomic performance in an eight-season experiment. Field Crops Res. 96, 252–259, **(2006)**.

20. Cabangon et al. Comparing water input and water productivity of transplanted and direct seeded rice production systems. Agric. Water Manage. 57, 11–13, **(2002)**.

21. Shi, Y. C. Way of exploitation: Biological water saving. Sci. Technol. Rev. 10, 3–5, **(1999).**

22. Lu et al. The effects of irrigation regimes on the water use, dry matter production and physiological responses of paddy rice. Plant Soil 223, 207–216, **(2000)**.

23. Belder et al. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agricultural Water Management 65 193–210, **(2004)**.

24. Serraj et al . Drought resistance improvement in rice: an integrated genetic and resource management strategy. Plant Production Science 14, 1–14, **(2011)**.

25. Zhang et al. Locating genomic regions associated with components of drought resistance in rice: Comparative mapping within and across species. Theor. Appl. Genet. 103, 19–29, **(2001)**.

26. Bueno et al. Water productivity of contrasting rice genotypes grown under water-saving conditions in the tropics and investigation of morphological traits for adaptation. Agricultural Water Management 98, 241–250,**(2010)**.

27. Uphoff et al. SRI as a methodology for raising crop and water productivity: productive adaptations in rice agronomy and irrigation water management. Paddy Water Environ. 9, 3–11, (**2010)**.

28. Uphoff et al. A critical assessment of a desk study comparing crop production systems: the example of the 'System of Rice Intensification' versus 'best management practice'. Field Crop Res. 108, 109–114, **(2008)**.

29. Moser C. M., and Barrett, C. B. The disappointing adoption dynamics of a yield increasing, low external input technology: the case of SRI in Madagascar. Agric. Syst. 76, 1085–1100, **(2003)**.

30. Thiyagarajan et al. The System of Rice Intensification in practice: Explaining low farmer adoption and high disadoption in Madagascar. In ''Water-Wise Rice Production'' (B. A. M. Bouman, H. Hengsdijk, B. Hardy, P. S. Bindraban, T. P. Tuong, and J. K. Ladha, Eds.). Proceedings of a Thematic Workshop on Water-Wise Rice Production, 8–11 April 2002 at IRRI Headquarters in Los Banos, Philippines **(2003)**.

31. Bouman et al. ''Water Management in Irrigated Rice—Coping with Water Scarcity.'' International Rice Research Institute, Los Banos, Philippines (**2007)**.

32. CIIFAD. The System of Rice Intensification Countries. Cornell International Institute for Food, Agriculture and Development. Ithica. http://sri.ciifad.cornell.edu/countries/index.html. **(2011)**.

33. Krupnika et al. Yield, water productivity and nutrient balances under the System of Rice Intensification and Recommended Management Practices in the Sahel. . Field Crop Res. 130, 155–167, **(2012)**.

34. Shen et al. Test and demonstration on wetcultivation with film mulching of rice. Hubei Agric. Sci. 5, 18–22, **(1997)**.

35. Kreye et al. Fluxes of methane and nitrous oxide in water-saving rice production in north China. Nutr. Cycl. Agroecosyst. 77, 293–304, **(2007)**.

36. Huang et al. Ecophysiological effect of dry cultivated and plastic film-mulched rice planting. Chin. J. Appl. Ecol. 10, 305–308 **(1999)**.

37. Borrell et al. Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. Field Crops Res. 52, 231–248, **(1997)**.

38. Kukal S. S., and Aggarwal, G. C. Puddling depth and intensity effects in rice–wheat system on a sandy loam soil. I. Development of subsurface compaction. Soil Till. Res. 72,1–8, **(2003)**.

39. Sandhu et al. Crop and water productivity of bed transplanted rice as influenced by various levels of nitrogen and irrigation in northwest India. Agric. Water Manage. 104, 32–39, **(2012)**.

40. Maynard, M. Permanent beds—Their potential role in soil management for the future. Farm. Newslett. Large Area 137, 14–18, **(1991)**.

41. Sayre, K. D., and Hobbs, P. R. The raised-bed system of cultivation for irrigated production conditions. In ‘‘Sustainable Agriculture and the International Rice–Wheat System’’ (R. Lal, P. R. Hobbs, N. Uphoff, and D. O. Hansen, Eds.). pp. 337–355.Marcel Dekker, New York **(2004)**.

42. Singh et al. The effect of seeding and tillage methods on productivity of rice–wheat cropping system. Soil Till. Res. 61, 125–131, **(2001)**.

43. Thompson et al. ‘‘Improving the Water Use Efficiency of Rice.’’ Final Report Project 1204. CRC for Sustainable Rice Production, Yanco, Australia (**2003)**.

44. Beecher et al. Effect of raised beds, irrigation and nitrogen management on growth, water use and yield of rice in south-eastern Australia. Aust. J. Exp. Agric. 46, 1363–1372, **(2006).**

45. Vories et al. Comparison of flooded and furrow irrigated rice on clay. Irrig. Sci. 21, 139–144, **(2002).**

46. Tuong et al. quantifying flow processes during land soaking of cracked rice soils. Soil Sci. Soc. Am. J. 60, 872-879, **(1996)**.

47. Tripathi, R. P. Water management in rice–wheat system. In ‘‘Rice–Wheat Cropping System’’ (R. K. Pandey, B. S. Dwivedi, and A. K. Sharm, Eds.). pp. 134–147. Project Directorate for Cropping Systems Research, Modipuram, India (**1996)**.

48. Lacy, J., and Wilkins, J. Increasing yields, water use efficiency and profit from Ricecheck. Farm. Newslett. Large Area 162, 64–66, **(2003)**.

49. Camp, C. R. Subsurface drip irrigation: A review. Trans. Am. Soc. Agric. Eng. 45, 1353–1367, **(1998)**.

50. Humphreys et al. The growth and nitrogen economy of rice under sprinkler and flood irrigation in south-east Australia. II. Soil moisture and mineral N transformations. Irrig. Sci. 10, 201–213 **(1989)**.

51. Simpson et al. Stable isotope ratios in irrigation water can estimate rice crop evaporation. Geophys. Res. Lett. 19, 377–380, (**1992)**.

52. Narang R. S. and Gulati H. S. On-farm water management. In ‘‘Proceedings of the Symposium on Water Management—Need for Public Awareness’’, pp. 117–129. Punjab Agricultural University, Ludhiana, India **(1995)**.

53. Ortiz-Monasterio et al. Date of sowing effects on grain and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. Field Crops Res. 37, 169–184, **(1994)**.

54. Shen Q. and Yangchun X. Cropping system N and water management: Aerobic barley in rotation with aerobic and waterlogged rice. Paper Presented at the FAO/IAEA Coordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice–Wheat Cropping System in Asia. IAEA, Vienna, Austria **(2003)**.

55. Bhushan et al. Saving of water and labor in a rice–wheat system with no-tillage and direct seeding technologies. Agron. J. 99, 1288–1296, **(2007)**.

56. Belder et al. Effect of water and nitrogen management on water use and yield of irrigated rice. Agric. Water Manage. 65:193-210 (**2004**).

57. Bueno et al. Water productivity of contrasting rice genotypes grown under water-saving conditions in the tropics and investigation of morphological traits for adaptation. Agricultural Water Management, 98(2), 241-250 (**2010**).

58. Yao et al. Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. Field Crops Research 126:16-22 (**2012**).

59. Bouman et al. Yield and water use of irrigated tropical aerobic rice systems. Agricultural Water Management 74 87–105, (**2005**).

60. Latif et al. Evaluation of management principles and performance of the System of Rice Intensification (SRI) in Bangladesh. Field Crops Research 114, 255–262, (**2009**).