Chapter 8
Rice Production Systems

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8.1 Introduction

Rice is one of the major staple cereals with more than 3.5 billion people depending on rice for more than 20 % of their daily calorie intake (IRRI, Africa Rice and CIAT 2010). It is estimated that the rice production must increase by 114 million tons by 2035, but farmers must achieve it under significant threats from climate change (Suzanne et al. 2012) coupled with decreasing amount of available agricultural land, labor, and water for agriculture and increased costs of all inputs. Increasing global food production with minimal adverse impact on resources and the environment is the greatest challenge for food security (Ladha et al. 2015). Hence, for ensuring food and nutritional security of the rice-growing world, it is essential to make consistent efforts to understand and develop innovative rice production systems that are resource use efficient, higher net income generating, and environment friendly.

This chapter attempts to summarize the information on rice production systems, resources used, crop productivity attained, the challenges encountered, and possible research needs for improving productivity in rice production systems, to meet the future food demands.

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8.2 Rice Production Systems Classified

Rice is grown in more than 100 countries spread across six continents and in a wide range of environments. Globally rice is grown on a total area of approximately 158 million ha, producing more than 700 million tons annually (470.6 million tons of milled rice) in 2015 (USDA 2016). About 90 % (nearly 640 million tons) of the rice in the world is grown in Asia (Fig. 8.1), with China and India as the lead producers. Africa and Latin America produce about 25 million tons each. In Asia and sub-Saharan Africa, almost all rice is grown on small farms of 0.5–3 ha per household. Rice is produced in many different environments and in many ways. The rice production systems were classified by different scientists, in different countries, and in different ways at different times, depending on the context. The environmental and socioeconomic conditions of rice production vary greatly from country to country as well as from location to location which affected the performance of rice production in the past and influences the potential of improving future rice production. Rice is cultivated under temperate, subtropical, and tropical climatic conditions with the weather varying from arid and semiarid to subhumid and humid. Based on soil water conditions, rice production ecosystems include irrigated lowland, irrigated upland, rainfed lowland, rainfed upland, and deep water/floating ecosystems (Fig. 8.2). Socioeconomically, farm size cultivated by a household in South Asia, Southeast Asia, East Asia, and Africa is generally small, which varies from less than 1 ha to few hectares. In the developed countries, the farm size is larger.

8.2.1 *Classification of Rice Production Systems Based on the Environment Where the Rice Is Grown*

The classifications of rice environments are based on altitude (upland, lowland, deep water) and water source (irrigated or rainfed).

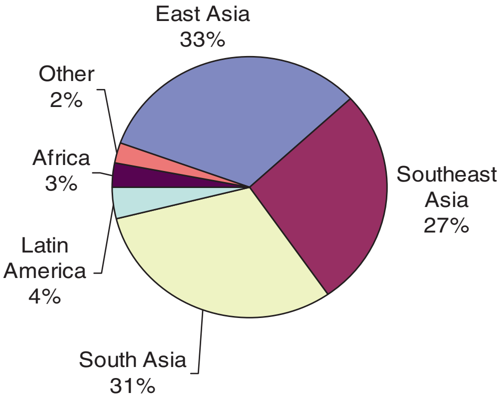

Fig. 8.1 Percent of global rice production by region. 2011 (www.irri.org)

1. *Lowland rice production system* – Continuously grown under flooding (paddy rice). Lowlands are further categorized as:

(i) *Irrigated lowland production system*: Irrigated lowland rice system produces 75 % of the global rice production from about 93 million ha. Asia has around 56 % of the world's all crops in total irrigated area, of which 40–46 % is of rice. Rice occupies 64–83 %, 46–52 %, and 30–35 % of the irrigated area in Southeast Asia, East Asia, and South Asia, respectively (GRiSP, 2013). The countries with the largest areas of irrigated lowland rice are China (31 M ha), India (19 M ha), Indonesia (7 M ha), and Vietnam (3 M ha) (Dobermann and Fairhurst 2000). Irrigated lowland rice production system is the most important rice production system for food security of Asian countries. The most common method of establishment of this production system is transplanting. Rice is also established by direct wet or water seeding in irrigated lowland production systems. In transplanting method of rice establishment, rice seedlings are raised in a rice seedling nursery for 20–40 days prior to their manual or mechanical transplanting into the flooded field. Irrigated rice is grown in bunded fields or paddies, which are surrounded by a small levee that keeps the water surrounded. The farmers, who have small holding (0.5 to 2 acres) of land, normally maintain in the field a water layer of 5–10 centimeters (cm) during the major period of the cropping cycle (Bouman et al. 2006). One or more rice crops can be grown per year as the water supply is assured. Rice–rice and rice-upland cropping systems are followed. Irrigated rice receives about 40 % of the world's irrigation water

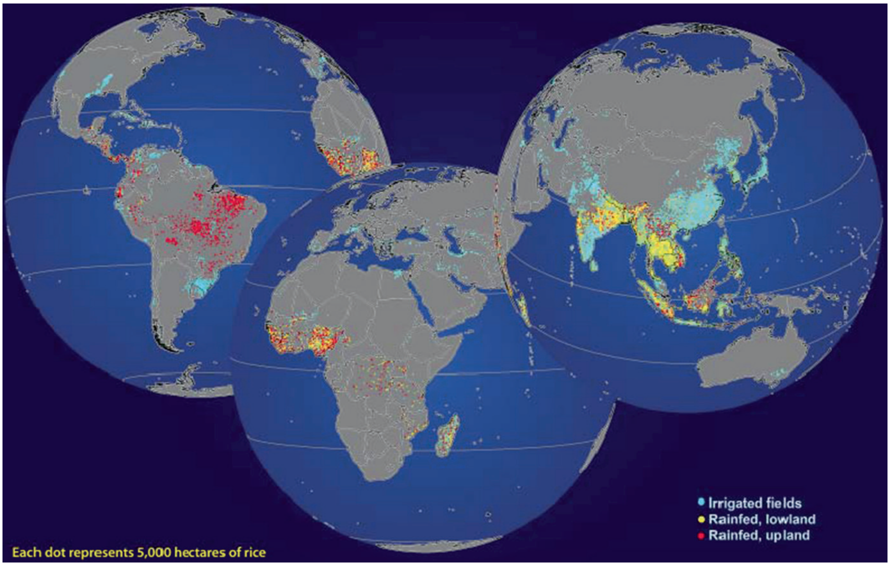

Fig. 8.2 Major global rice-growing areas and ecosystems (GRiSP 2013)

and 30 % of the world's developed freshwater resources. The average productivity of irrigated lowland rice is higher (about 5.4 t/ha) (GRiSP 2013).

Rice is grown under irrigated systems in temperate climatic conditions of Australia, Bhutan, Central Asia (Kazakhstan and Uzbekistan), Chile, China, Japan, Korea, Nepal, Russia, Turkey, the USA, and Uruguay (Jena and Hardy 2012). In Bhutan, Nepal, and part of China, rice is established by transplanting. In the irrigated lowlands of Korea, rice is mostly established by machine transplanting method with hand transplanting practiced on only 1.2 % of marginal rice land. However, with decreased labor availability and rising labor cost, farmers are motivated to shift from transplanting to direct seeding as is practiced in other temperate rice-growing countries. In temperate climatic regions where a single irrigated rice crop is grown per year, productivity of 8–10 t/ha or more is achieved (http://ricepedia.org/rice-as-a-crop/where-is-rice-grown).

(ii) *Rainfed lowland production system (including flood prone)*: Rainfed lowland rice is grown in river deltas and coastal areas of South Asia, parts of Southeast Asia, and essentially all of Africa, where the fields are bunded and flooded with rainwater for at least a part of the cropping season. In this system, the major method of rice establishment is transplanting, but direct wet or dry seeding is also practiced. Globally, around 19 % of the world's rice is produced from 52 million ha of rainfed lowlands (GRiSP 2013). Abiotic stresses, such as drought (in around 27 million ha) and uncontrolled flooding ranging from short-duration flash floods to deep water submergence with 100 cm of water for a few months (20 million ha), prevail due to highly uncertain rainfall and salinity (Dobermann and Fairhurst 2000; Bouman et al. 2005; Wassmann et al. 2009; Clermont-Dauphin et al. 2010; Mackill et al. 2010). Water is 1 to 5 m deep and is supplied by rivers, lakes, or tides in river mouth deltas. Water depth may exceed 5 m in some parts of Bangladesh, as well as in the Mekong, Kariba Dam (Tongas), and Niger deltas. Deep water or floating rice is established by broadcasting rice seed in plowed fields and is normally grown unbunded, in regions where the water level rises quickly after the beginning of the monsoon. Traditional long tiller and few sprout varieties are cultivated. The rice plants elongate and float as the floodwater advances; thus, it is named as "floating rice." Due to the risk involved in growing rice in these most difficult environments, farmers tend to use fertilizers rarely and avoid using improved rice varieties. Thus the rice productivity in rainfed lowland areas is very low (1–2.5 t/ha) (Dobermann and Fairhurst 2000).

2. *Rainfed upland rice production system* – In this system the rice is grown under high rainfall. Rainfed upland rice production system is often used by subsistence farmers in Asia, Africa, and Central America. It can be found in environments ranging from low-lying valley bottoms to steep sloping lands with high runoff. The rice in this system is established by broadcasting or dibbling in dry soil prior to the onset of monsoon or during the rainy season. The aerobic condition prevails in the soil throughout the rice cropping season. Traditionally, one rice crop

is grown annually with minimal input application. Of rice produced in around 15 million ha, rainfed uplands account for about 4 % of the global total rice production (GRiSP 2013). Two-third of rainfed upland rice is in Asia (Bangladesh, Cambodia, China, India, Indonesia, Myanmar, Thailand, and Vietnam). In the rice belt of Africa, upland areas of central and western part represent about 40 % of the African area under rice cultivation and employ about 70 % of the region's rice farmers (Bouman et al. 2007). The ecosystem is extremely diverse, including fields that are level, gently rolling, or steep, at altitudes of up to 2000 m and with rainfall ranging from 1000 to 4500 mm annually. Soils range from highly fertile to highly weathered, infertile, and acidic, but only 15 % of total upland rice grows where soils are fertile and the growing season is long. The productivity of upland rainfed rice is low (about 1 t/ha) because of many biotic, abiotic, and social constraints and the use of the local varieties by farmers that fail to respond to improved management practices. The major constraints of this system are drought, problem soils, and pests (weeds, diseases, insects, nematodes) (Bouman et al. 2007; GRiSP 2013).

3. *Irrigated upland or aerobic rice production system* – In aerobic rice systems, the rice plant is established by direct seeding in non-puddled, non-flooded fields and managed intensively as an upland crop (Tuong and Bouman 2003). Aerobic rice systems can reduce water requirements for rice production by over 44 % relative to conventionally transplanted systems, by reducing percolation, seepage, and evaporation losses, while maintaining yields at an acceptable level (Bouman et al. 2005). There were efforts in the 1980s to develop and popularize the irrigated upland rice or aerobic rice production in Brazil using sprinkler irrigation systems. In northern China, aerobic rice production is being practiced currently at a limited scale in freely drained fields, as a response to water shortage. The areas planted with aerobic rice varieties were estimated to be about 80,000 ha in China and 250,000 ha in Brazil (http://www.fao.org/agriculture /crops /thematic-sitemap/ theme/spi/scpi-home/managing-ecosystems/sustainable-rice-systems/rice-what/en/). In India, the aerobic rice system adoption has been initiated in states like Karnataka (Rao et al. 2015).

8.2.2 Classification of Rice Production Systems Based on the Method of Rice Establishment

The major methods of rice establishment in the world are transplanting and direct seeding. Thus, based on the method of rice establishment, the rice production systems may be categorized as (a) transplanted rice (TPR) production systems and (b) direct-seeded rice production systems. Direct-seeded rice production systems may be further categorized as (i) dry-seeded rice (dry-DSR) production system, (ii) wet-seeded rice (wet-DSR) production system, and (iii) water-seeded rice (water-DSR) production system. These production systems are briefly described below.

8.2.2.1 Transplanted Rice (TPR) Production System

Rice is commonly grown by transplanting seedlings into the puddled soil (wet tillage) in lowlands of Asia (e.g., India, Indonesia, Bangladesh, Myanmar) and Africa (e.g., Madagascar, Mali). Transplanting of rice is done manually (Fig. 8.3) or by machine (Fig. 8.4). The manual transplanting method involves growing of seedlings in a nursery and replanting of 20–30-day-old rice seedlings to puddled soils. The rice seedling nursery may be raised on wet bed or dry bed or dapog or mat or modified mat methods depending on the locality, soil type, rice ecosystem, and the resource availability (for details, refer to http://www.knowledgebank.irri.org/step-by-step-production/growth/planting). In several Asian countries, the labor-intensive transplanted rice production systems are being practiced until now, where even the labor supply is abundant due to the population growth. For machine transplanting the rice seedlings are grown in trays or in mat-type nursery in which a thin layer of sol mixed with farm yard manure or compost is placed on a polythene sheet and rice seedlings are raised. Mats of rice seedlings from the trays or mat-type nursery are used for machine transplanting. In Asia, machine transplanters are now being used to establish rice crops in China, Japan, Korea, and Taiwan. In India, farmers started using it in states like Karnataka and Andhra Pradesh. The traditional TPR production system

Fig. 8.3 The manual transplanting method of rice establishment uses more labor, water, and energy as it involves processes such as rice seedling nursery raising, seedling pulling, and transplanting in flooded soil conditions (Photos by A.N. Rao)

has advantages such as adequate nutrient availability (e.g., phosphorus, zinc, iron) due to creation of anaerobic conditions (Sanchez 1973), assured seedling establishment, initial seedling vigor, and competitiveness against weeds (Rao et al. 2007). However, higher quantities of water are consumed in TPR in order to accomplish the processes such as puddling, surface evaporation, and percolation (Farooq et al. 2011). This production system is labor, water, and energy intensive and is becoming less profitable as these resources are becoming increasingly scarce. It also deteriorates the physical properties of soil, adversely affects the performance of succeeding upland crops, and contributes to methane emissions. However, TPR continues to dominate under certain environmental and socioeconomic conditions of the world.

8.2.2.2 Direct-Seeded Rice (DSR) Production System

Direct seeding of rice is done by (1) dry seeding (dry-DSR), (2) wet seeding (wet-DSR), and (3) water seeding (water-DSR) (Kumar and Ladha 2011). As the rice seeds are sown directly, the dry- , wet- and water-DSR methods are often jointly referred to as DSR. At present 23 % of rice area is direct-seeded globally (Rao et al.

Fig. 8.4 Rice establishment by using transplanting machine reduces the drudgery of women labor, reduces the cost of cultivation, and ensures optimum rice plant population (Photos by A.N. Rao)

2007; Kumar and Ladha 2011). Dry-DSR consists of sowing dry seeds on dry (unsaturated) soils. Seeds can be broadcasted, drilled, or dibbled. Dry-DSR production is practiced traditionally in most of the Asian countries in rainfed upland ecosystems and is also used in irrigated areas with precise water control as aerobic rice. In certain states of India, farmers are cultivating dry-DSR with the onset of monsoon and convert it to irrigated lowland rice after release of the assured canal water in the system (Fig. 8.5) (Rao et al. 2015). Dry-DSR and TPR in the furrow-irrigated raised-bed planting system were also tested (Singh et al. 2006, 2008) for attaining optimal water productivity in the rice–wheat system in the Indo-Gangetic Plains of South Asia. However, rice establishment on furrow-irrigated raised-beds is not currently popular among the rice farming community.

Wet-DSR involves sowing of pre-germinated rice seeds in wet (saturated) puddled soils. Wet- DSR is done by broadcasting the seeds on puddled soil or by using a drum seeder (Fig. 8.6). Wet-DSR is practiced in favorable rainfed lowlands and irrigated area with good facility of drainage as in Malaysia, Thailand, Vietnam, the Philippines, and Sri Lanka (Pandey and Velasco 2005; Weerakoon et al. 2011). DSR is becoming an attractive alternative to TPR. Asian rice farmers are shifting to DSR to reduce labor input, drudgery, and cultivation cost (Rao et al. 2007; Kumar and Ladha, 2011).The increased availability of short-duration rice varieties and cost-efficient selective herbicides has encouraged farmers to try this method of establishing rice (Balasubramanian and Hill 2002). It is quickly replacing traditional

Fig. 8.5 Dry-seeded irrigated rice sown by using seed cum fertilizer drill (Photos by A.N. Rao)

Fig. 8.6 (**a**) The drum seeder and (**b**) the crop of wet-seeded rice (*left*) sown by using the drum seeder (Photos by A.N. Rao)

transplanting in areas with good drainage and water control (Balasubramanian and Hill 2002). Rice is mostly direct-seeded, with only 6 % area under transplanting, in Latin America (GRiSP 2013). In the water-DSR, pre-germinated rice seeds (soaked and incubated for 24 h each) are broadcast in standing water on puddled (wet-water-DSR) or unpuddled soil (dry-water-DSR). The relatively heavyweight rice seeds sink in standing water, resulting in good anchorage. Water-DSR is used for rice establishment in irrigated lowland areas with good land leveling as in California (United States), Australia, and European countries specifically for managing problematic weeds such as weedy rice. In Asia, some countries like Malaysia are adopting it.

In this chapter, the method of rice establishment is considered as the major criteria for classifying rice production systems. The information of these rice production systems on the attained crop productivity, the resources used, and the challenges encountered will be discussed while highlighting the possible research needs for improving productivity in rice production systems to meet the future food demands.

8.3 Productivity of Different Rice Production Systems

Several studies have shown that productivity of TPR and DSR rice will be similar in a given environment provided that they are cultivated using best management practices (Rickman et al. 2001; Mitchell et al. 2004; Kumar and Ladha 2011). Traditionally under rainfed TPR areas, need of ponded water for customary practice of puddling delays rice transplanting by 1–3 weeks (Ladha et al. 2009) resulting in reduced yields. The puddled TPR production systems need a large quantity of water and labor, which are becoming scarce and costly, in addition to the drudgery to transplanting women and children. The profit margins were also reduced due to increasing water and labor cost for TPR (Pandey and Velasco 1999). Hence, a major shift from puddled TPR production system to DSR system is taking place in the irrigated areas of many developing countries in Asia (Pandey and Velasco 2005 , Rao et al. 2007). However, compared to TPR, lower yield was reported with wet- and dry-DSR production systems due to uneven or poor crop establishment; inadequate weed control; higher spikelet sterility than in puddled transplanting; higher crop lodging, especially in wet seeding and broadcasting; and micronutrient deficiencies (Rickman et al. 2001; Rao et al. 2007; Choudhury et al. 2007; Singh et al. 2005). Higher rice productivity was reported when these constraints were alleviated (Bhushan et al. 2007; Yoshinaga 2005).

The performance of different types of DSR production systems varied with countries depending on the cultural practices used, the environment, and their interaction (Kumar and Ladha 2011). Among DSR production systems, line/drill seeding (compared with broadcasting) and wet-DSR (compared with dry-DSR) were reported to yield higher. However, dry-DSR was found to be more resistant to drought with longer survival under drought period and may increase yield stability of rainfed rice than the wet-DSR and transplanted rice systems (Boling et al. 1998). The yield of dry-DSR and TPR systems were similar when irrigation was scheduled daily or at 20 kPa (Yadav et al. 2011a). In China, a meta-analysis revealed that the rice grain yield decreased in rice–rice cropping system and increased in rice-upland cropping system due to the adoption of zero tillage (ZT) (Huang et al. 2015), when compared to conventional tillage (CT). The responses of rice grain yield to ZT did not differ with rice establishment method (TPR or DSR), rice cultivar type (hybrid or inbred), ZT adoption duration (<3 years or 3–6 years or >6 years), and management of crop residues (residues removed or retained) (Huang et al. 2015).

Based on the data of several studies they reviewed, Kumar and Ladha (2011) reported that direct-seeded rice production systems had a lower cost of production by US\$ 22–80 ha^{-1} resulting in higher economic returns of US\$30–50 ha^{-1}compared with conventional puddled TPR production system. They reported the savings in production costs increased in the following order: ZT-dry-DSR > Bed-dry-DSR >CT-dry-DSR > CT-wet-DSR > CT-TPR.

8.4 Resource Use of Different Rice Production Systems

High cost of production and diminishing resources have led to a greater focus on improving the overall eco-efficiencies of agricultural systems (Keating et al. 2010) for achieving optimal agricultural outputs using less land, water, nutrients, energy, labor, and capital inputs in rice production systems.

8.4.1 Water

Irrigated lowland rice is typically grown under flooded conditions, and at the field level, it utilizes up to two to three times more water than other major food crops, due to the unproductive water flows, in the form of seepage and percolation to drains, creeks, or groundwater. This can amount to 60–80 % of all water inputs to rice (Tabbal et al. 2002). The water input for a typical puddled TPR per season was estimated to vary from 660 to 5280 mm depending on the growing season, climatic conditions, soil type, and hydrological conditions, with 1000–2000 mm as a typical value in most cases (Tuong and Bouman 2003). The overexploitation of groundwater to meet the high water requirement of TPR and water scarcity has become a major threat to the sustainability of rice production (Rijsberman 2006). The per capita availability of water is expected to decline by 15–54 % over the next 35 years in several countries of Asia (Gleick 1993), and by 2025, 15–20 million ha of rice lands will suffer some degree of water scarcity (GriSP 2013). Hence, increasing water use efficiency in rice production systems is essential (Ladha et al. 2015). In addition to the consumption of large amount of irrigation water and labor, the process of puddling results in subsurface compaction (Kukal and Aggarwal 2003).

The increasing shortage of water resources has led to the development and adoption of aerobic rice system, which saves water input and increases water productivity by reducing water use during land preparation and limiting seepage, percolation, and evaporation (Nie et al. 2012). In an aerobic rice system, the crop can be dry direct-seeded or transplanted and soils are kept aerobic through the major part of the growing season. Supplemental irrigation is applied when needed. Aerobic rice cultivars are adapted to aerobic soils and have higher yield potential than traditional upland cultivars. Grain yields of 5–6 t ha^{-1} can be reached in aerobic rice system (Nie et al. 2012).The micronutrient deficiencies such as Zn and Fe in aerobic rice are of major concern (Gao et al. 2006). Aerobic rice could considerably improve eco-efficiency in rice-based systems where water, labor, and energy are becoming increasingly scarce, and hence it is gaining importance in South Asia as an alternative to the conventional transplanted flooded rice system (Mahajan et al. 2013).

Dry-DSR production system helps to save irrigation water, especially in fine-textured soils (Yadav et al. 2011a, b). Dry-DSR with intermittent irrigation offers potential water savings at the field level due to reduced evaporation losses, intermittent irrigation, and avoidance of puddling. In dry-DSR and TPR production systems, significant irrigation water input decline was recorded with irrigation at 20 kPa compared to daily irrigation (Yadav et al. 2011a). Novel irrigation water-saving technologies such as alternate wetting and drying (AWD) can also help many rice farmers around the world to cope with water scarcity (Lampayan et al. 2015). In AWD, irrigation is given at intervals of 6–8 days for heavy soils and 4–5 days for lighter soils. Prior to next irrigation, the soil dries naturally after the water disappearance from soil surface and the water quantity applied at each of the irrigation is about 50–60 mm. Thus, the introduction of aerobic periods during the growing season and altering soil chemistry and flooding practices results in reduced water use (Yao et al. 2012; Liu et al. 2013) and reduced global warming potential (GWP) of greenhouse gas (GHG) fluxes (Feng et al. 2013). A 10–77 % saving in water and 20–87 % increase in rice yield with the additional advantages of energy saving, nutrient use efficiencies, and controlling vectors of malaria and Japanese encephalitis were reported with the use of AWD (Van der Hoek et al. 2001). The irrigation at 20 kPa lowered the irrigation water use of dry-DSR, with AWD, by 33–53 % as compared to the respective transplanted rice system (Yadav et al., 2011a).

8.4.2 Nutrients

Of all the nutrients, nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) remain the major nutrients for increased and sustained rice productivity. The fertilizer use trend in rice indicates the highest consumptions of N fertilizer followed by P_2O_5 and K_2O fertilizers with imbalanced fertilizer use (i.e., very high use of N, less use of P_2O_5, and negligible use of K_2O, S, and micronutrients), increased soil nutrient mining, and decreased soil organic matter and soil fertility (FAO 2006). Proper nutrient management should aim to supply fertilizers adequate for the demand of the rice and applied in ways that minimize loss, maximize the efficiency of use, and improve the productivity and sustainability of rice production systems, because of the high potential for loss and economic and environmental consequences (Chien et al. 2009). The nutrient management strategies for irrigated and rainfed lowland rice production systems vary (Dobermann and White 1999).

Among macronutrients, N is a key nutrient for the optimal rice growth and development to attain optimal rice yield. The rice crop and water management practices for DSR differ considerably from those for TPR. The DSR may have higher nitrogen requirement due to the longer duration of DSR in fields than puddle transplanted rice (Kumar and Ladha 2011).The insufficient N uptake by the DSR crop and resulting lower yield observed in DSR production systems (Kropff et al. 1994) was reported to be due to relatively lower uptake of nitrogen by the shallower roots of DSR (Zhang and Wang 2002) and higher leaching losses of applied nitrogen out of root zone in DSR (Ponnamperuma 1972). Increasing nitrogen quantity in DSR in larger number of splits with optimum irrigation may lead to higher rice yield due to their effect on the nitrogen movement and availability to plants in soils especially in coarse- and medium-textured soils (Shad and De Datta 1988).

N is applied in the larger quantities compared to all other nutrients as most soils of rice production systems are nitrogen deficient. As per global estimates, the fertilizer N recovery by the crop averages only 46 % in rice systems (Ladha et al. 2005). To increase the N use efficiency of irrigated rice, site-specific N management (SSNM) was developed (Dobermann et al. 2002), in which N application is based on the demand of the crop for N as measured by the chlorophyll meter (SPAD) or leaf color chart (Peng et al. 1996). The usefulness of leaf color chart for dry-DSR rainfed lowland rice and wet-DSR was reported by Budhar and Tamilselvan (2003) and Angadi et al. (2002). SSNM was evaluated in farmers' fields in eight major irrigated rice domains in Asia, and the average grain yield increased by 11 % with an increase in average recovery efficiency from 31 % to 40 % and 20 % of all farmers achieving more than 50 % recovery efficiency (Dobermann et al. 2002). Enhanced efficiency nitrogen fertilizers have been developed to decrease N losses and improve N use efficiency in rice production systems (Linquist et al. 2013).

On an average, around 18 kg ha^{-1} of K_2O for the irrigated rice crop is needed (Dobermann and Cassman 1997). K_2O deficiency has become a constraint in soils that were previously not considered as K_2O limiting. The occurrence of K_2O deficiency and response to applied K_2O depend on the yield levels, K_2O buffering capacity of the soil, straw management, and net K_2O inputs from sources other than fertilizer (Dobermann et al. 1996). Clay mineralogy, texture, and K_2O inputs from irrigation or rainwater are needed to be considered along with K_2O inputs from other sources while formulating a rational K_2O management strategy for the rice production systems (Dobermann et al. 1998).

In the irrigated rice production systems, P_2O_5 solubilizes immediately after flooding, leading to an increase in available P_2O_5 to rice (Kirk et al. 1990). However, soil drying reduces its availability to crop (Willet and Higgens 1978; Sah et al. 1989). Hence, phosphorus deficiency is important in drought-prone environments because the mobility of P_2O_5 decreases sharply as soil dries. In systems of low P_2O_5 fertility, the repeated dry-wet transition increases P_2O_5 extraction, further lowering fertility. The upland rice dry-DSR is generally grown on poorly fertile, strongly weathered soil, with high P_2O_5 fixation and severe soil acidity. P_2O_5 deficiency is one of the key constraints of upland dry-DSR production (Gupta and O'Toole 1986). Banding of P_2O_5 fertilizer beneath the dry-DSR crop row is preferred.

The deficiency of secondary and micronutrients is often stimulated by the application of large amounts of N, P_2O_5, and K_2O for achieving higher rice yield targets (Johnston et al. 2009). Iron (Fe) is only slightly soluble in the soil under aerobic conditions, especially in alkaline calcareous soils (Marschner 1995). Fe deficiency is a common nutritional problem in the production of aerobic rice. Current crop management strategies addressing Fe deficiency include Fe foliar application, plant breeding for enriched Fe rice varieties, and adoption of cropping systems (Zuo and Zhang 2011). Across the globe, among micronutrients, zinc (Zn) deficiency is one of the important abiotic factors limiting rice productivity in addition to being a major nutritional disorder affecting human health (Alloway 2009). Zn deficiency is wide spread in traditional lowland (Dobermann and Fairhurst 2000) due to high soil pH and high carbonate content as well as low redox potential (Forno et al. 1975; Alloway 2009). Shifting the method of establishment from TPR to DSR or aerobic rice system and adoption of water-saving technologies like AWD may decrease Zn availability (Gao et al. 2006). Soil or foliar Zn fertilizers application is used to manage Zn deficiency (Rengel et al. 1999) and to increase grain Zn concentration (Jiang et al. 2008). It is essential to utilize breeding programs to increase Zn uptake and utilization in rice production systems as a large genotypic variation (13.5–58.4 mg kg^{-1}) was recorded in Zn grain concentration with differential rice genotypic responses to Zn deficiency (Graham et al. 1999; Quijano-Guerta et al. 2002; Shi et al. 2009; Gao et al. 2009).

It is essential to have a proper blend of organic and inorganic fertilizers for increasing the productivity of rice production systems and for improving soil health. Application of SSNM can help improve nutrient management in rice production systems and attain improved yields and profitability as SSNM is based on scientific principles for optimal site-specific and need-based supply of nutrients to rice in a particular cropping season.

8.5 Pests (Insects, Diseases, and Weeds) and Their Management in Different Rice Production Systems

The estimated average potential yield loss in major crops globally is 18 %, 16 %, and 34 % due to animal pests, (non-virus) pathogens, and weeds, respectively, in the absence of any physical, biological, or chemical crop protection (Oerke 2006). The potentially highest yield loss causing weeds are more problematic in the DSR production system than in puddled TPR production system. The young emerging rice seedlings of DSR do not possess a competitive advantage over weeds as do have the transplanted 30-day-old seedlings in the TPR. Moreover, a layer of water suppresses the initial flushes of weeds in TPR, and lack of flooding in DSR provides a competitive advantage to weeds over rice seedlings in DSR (Rao et al. 2007, Rao and Nagamani 2007). In addition to currently problematic weeds such *Echinochloa* spp., weedy rice is becoming a major threat to dry-DSR production systems which replaced traditional transplanted rice production systems (Rao and Nagamani 2007). Hence, integrated weed management strategies are to be developed for managing the weedy-rice problem in dry-DSR production systems.

A study in tropical Asia covering a wide range of lowland rice-cultivating environments revealed that the injury profiles were dominated by stem rot and sheath blight; bacterial leaf blight, plant hoppers, and leaf folder; and sheath rot, brown spot, leaf blast, and neck blast (Savary et al. 2000). Stem rot and sheath blight were associated with high (mineral) fertilizer inputs, long fallow periods, low pesticide use, and good water management in (mostly) transplanted rice crops of a rice–rice rotation. Bacterial leaf blight, plant hoppers, and leaf folder were more prevalent in direct-seeded rice–rice production system with poor water management and lower fertilizer and pesticide input use or with adequate water management and higher fertilizer and pesticide input usage. Sheath rot, brown spot, leaf blast, and neck blast correspond to low-input, labor-intensive (hand weeding and transplanting) rice crops in a diverse rotation system with uncertain water supply. Weed infestation is an omnipresent constraint. The high weed pressure, severe iron deficiency, and nematode infestation coupled with higher irrigation water inputs were reported to be the reasons for getting rice yields lower than the transplanted rice by the adoption of dry-seeded rice with most frequent irrigations on coarse- and medium-textured soils (Singh et al. 2015).

The rice production systems were reported to differ in the incidence and losses caused due to the pests. A Korean study revealed higher population densities of green rice leafhopper (*Nephotettix cincticeps*) and leaf folders (*Cnaphalocrocis medinalis*) in machine-transplanted than in direct-seeded rice, while abundance of brown plant hopper (*Nilaparvata lugens*) and small brown plant hopper (*Laodelphax striatellus*) was more in dry-DSR (Lee and Ma 1997). However, incidence of the Asiatic rice borer or striped rice stem borer (*Chilo suppressalis*), white-backed plant hopper (WBPH) (*Sogatella furcifera*), and rice stem maggot (*Chlorops oryzae*) did not differ among machine-transplanted and direct-seeded rice production systems (Lee and Ma 1997). In Punjab (India), the leaf folder incidence was higher in the bed-transplanted (BT) (8.87 %) and wet-seeded rice (WSR) (10.62 %) than that in rice grown using the other crop establishment methods (Sarao and Mahal 2013). The incidence of stem borer causing dead heart damage was significantly higher in the WSR system (5.85 %), while that of whitehead damage was higher in the BT (5.89 %) and WSR (6.54 %) plots than in other rice production systems. In Korea, sheath blight (*Rhizoctonia solani*) incidence was not affected by different rice production systems, while the incidence of rice blast (*Magnaporthe grisea*) was affected and favored by unbalanced nutrient contents in the rice plants (especially low SiO_2 and high nitrogen) and high leaf area index (LAI) (Kim et al.1996).

Integrated weed management strategies are available for managing weeds of different rice production systems (Rao 2010; Rao and Ladha 2011, 2013; Rao and Nagamani 2007, 2010; Rao et al. 2007, 2015). The management aspects of the diseases and insect pests of rice are dealt with in other chapters of this book.

8.6 Environmental Footprint by Different Rice Production Systems

Among different sectors that contribute to total greenhouse gas emissions of the world, contribution of agriculture is around 9.3 %, including 1.5 % of rice. Emissions of greenhouse gases (GHGs) from rice fields are common in South, East, and Southeast Asia. Rice ecosystems emit both CH_4 and N_2O and have higher global warming potential (GWP) of GHG emissions and have higher GWP_Y (GWP per unit of yield) than other crops as rice is grown usually under flooded conditions in irrigated ecosystems and uses more water (Linquist et al. 2012).

Due to individual or combined effects of various factors such as soil characteristics, climatic conditions, and management such as soil pH, redox potential, soil texture, soil salinity, temperature, rainfall, and water management, amount of CH_4 emission varies between different rice production systems depending on the rice establishment techniques (Harada et al. 2007; Ladha et al. 2015). The irrigated puddled TPR is considered one of the major sources of methane (CH_4) emissions and accounts for 10–20 % (50–100 Tg year $^{-1}$) of total global annual CH_4 emissions (Reiner and Aulakh 2000). Direct seeding has the potential to decrease CH_4 emissions (Wassmann et al. 2004). CH_4 emissions were reported to be lower in DSR than with conventional TPR (Gupta et al. 2002; Tyagi et al. 2010). In wet-DSR, the reduction in CH_4 emission increased from 16–22 % under continuous flooding to 82–92 % under mid-season drainage or intermittent irrigation as compared with conventional TPR under continuous flooding (Corton et al. 2000). CH_4 gas emission and global warming potential were maximum under conventional TPR, and emission of N_2O was maximum under DSR crop with conservation practice of brown manuring as the addition of organic matter to soil increased the decomposition rate, which resulted in higher emission of GHGs (Bhatia et al. 2011). One of the ways, to minimize CH_4 emissions while attaining equivalent or higher rice yield and lower irrigation water use than those of farmer-managed puddled TPR, is adoption of dry-

DSR with best management practices and conservation agriculture (CA) that uses ZT or minimum till while retaining rotational crop residues (Ladha et al. 2015). Izaurralde et al. (2004) opined that soils under ZT, depending on the management, might also emit less nitrous oxide.

8.7 Challenges and Future Research Needs of Different Rice Production Systems

The challenges vary with the rice production systems. The main factors that limit the yield in irrigated areas include poor management of inputs and resources; losses from weeds, pests, and diseases; inadequate land and water scarcity; and resulting salinity and alkalinity. In rainfed lowlands the challenges include adverse climate, drought, submergence, poor soils, pests, weeds, and absence of appropriate soil, water, crop management technologies, or strategies to suit the farmers' needs and which economically increase rice productivity. In upland dry-DSR environment, the major challenges are the biological constraints such as weeds, nematodes, and diseases (e.g., blast), poor soil fertility, socioeconomic constraints, and lack of productive varieties to suit the microenvironment of uplands and the drought. In TPR production systems, inappropriate management of problem soils, non-judicious use of fertilizers and water, and resulting pest proliferations and increasing cost of cultivation are major challenges. In aerobic rice production systems, lack of fine-tuned need-based technologies suited to different rice ecosystems across globe, non-availability of suitable varieties, micronutrient deficiencies, soil and water management optimization, adaptive weed menace, and pest problems are major challenges.

The future research efforts on rice production systems should ultimately result in (i) evolving practical integrated crop management strategies that improve rice productivity and production efficiently, effectively, and economically in different rice production systems across the globe and (ii) improving the food security and livelihood of the farmers and farming community of rice and rice-based cropping systems globally.

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