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Preface

Rice is among the three most important grain crops in the world, and it has a major contribution to fulfill the food needs across the globe. The role of rice crop is inevitable in the current and future global food security. Rice is grown in Asia, Americas, Australia, Europe, and Africa following diverse production practices. Pests and other problems, genotypes, and management practices in rice vary greatly in different parts of the world. Such difference are needed to be highlighted in order to understand and improve the global rice production. Our book 'Rice Production Worldwide' will help the readers to understand the past trends in global rice production, the current cultures of rice production in a global perspective, and the changes that are required to improve and sustain the rice productivity in different regions. In this book, we have addressed the rice origin, history, role in global food security, rice physiology, major rice producing areas of world (their importance, characteristics of rice cropping systems, management practices; salient technologies involved, merits and demerits of the particular systems), major rice production systems (conventional flooded system, aerobic rice system. etc.), rice cultivars, fertilizer management, and pest management in rice. Further, we have highlighted the harvesting, threshing, and processing of rice as well as the role of biotechnology in improving the rice production, quality, and nutrition. The book is equally advantageous for academicians, researchers, students, and farming community.

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Chapter 1
Current Status, Challenges, and Opportunities in Rice Production

Rajendra Prasad, Yashbir Singh Shivay, and Dinesh Kumar

1.1 Introduction

Rice is grown in all the six continents of the world (Asia, Africa, Australia, Europe, North America, South America) where field crop production is practiced leaving only the icy continent of Antarctica, where no crops are grown. Rice is the staple food for nearly half of the world's population. Rice has been a part of the cultural identities of several countries, and a number of festivals are related to the rich harvest of rice, e.g., Pongal, Onam, and Bihu in India, Rub Kwan Khao in central Thailand (www.ricewisom.com), Harvest Moon in China and Chu Suk in Korea (everything ESL.net), Dewi Sri in Indonesia, Santabary festival in Madagascar, and Amu festival in Ghana. In these festivals, the first grains of rice are offered to veneration God. Rice harvest festivals are also organized in southern states of the USA, namely, Arkansas and Louisiana, as a fair with lots of fun, food, and merrymaking. Rice is mentioned in Rig Veda and Mahabharata (Nene 2012; Prasad et al. 2016) and in the Bible (Rubin 2004).

Rice has now become a foreign exchange earner for several countries and is playing a role in their economies. Top ten rice exporting countries in 2014 were India, Thailand, Pakistan, the USA, SR Vietnam, Italy, Uruguay, Brazil, China, and Australia, respectively (Table 1.1) (Workman 2015). The largest rice importing regions are Middle East and sub-Saharan and Western Africa (Adjao and Staatz 2015).

In recent years, there have been three major studies on probable trends in the rice markets over the coming decades, namely, USDA (2013) for the period 2011–2022, University of Arkansas, USA (Wailes and Chavez 2012), and OECD/FAO (2013).

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Table 1.1 Global rice export during 2014

Country	*D* value (million US$)	Share (% of the world)
India	7906	32.1
Thailand	5439	22.1
Pakistan	2200	8.9
USA	2047	8.3
SR Vietnam	1713	6.9
Italy	699	2.8
Uruguay	524	2.1
Brazil	397	1.6
China	378	1.5
Australia	353	1.4

(Workman 2015)

The general conclusions are as follows: (1) Asia will continue to dominate the world rice economy, and (2) likely increase in world rice consumption is expected at 1 % per annum (pa); the rates may be higher in the Middle East and sub-Saharan Africa. According to OECD/FAO projections, rice–coarse grain price ratio may fall from 2.5 in recent years to 1.9 by 2022, and the rice–wheat price ratio may fall marginally from 1.8 to 1.7. This indicates some disadvantage to rice over coarse grains.

Success of the Green Revolution in the late 1960s witnessed a steady rise in Asia's per capita rice consumption, where it increased from 85 kg per year in the early 1960s to nearly 103 kg in the early 1990s. During the same period, global per capita rice consumption increased from 50 to 65 kg per annum. During this period (1960s–1990s), the global rice consumption increased from 150 to 350 million metric tons (MMT) due to two factors: (1) increased per capita rice consumption and (2) more than twofold increase in Asia's population. However, since the early 1990s, strong economic growth in many Asian countries, particularly in China and India, halted the upward trend in global per capita rice consumption as consumers diversified their diet from rice to high-value products such as meat, dairy products, fruits, and vegetables. A recent analysis has shown a declining trend in the contribution of rice toward total calorie intake by humans in Asian countries; the contribution of rice toward total calorie intake by humans changed from 30.2 % in 1961 to 26.8 % in 2007 in China, while it changed from 79.1 % in 1961 to 69.8 % in 2007 in Bangladesh (Timmer 2010). In 1961, the contribution of rice toward total calorie intake was 30.2 % in China and 79.1 % in Bangladesh, and in 2007 it was declined to 26.8 % in China and 69.8 % in Bangladesh. It is predicted that this trend will provide a check and limit the demand for rice to 501 MMT as against a production of 502.7 MMT in 2021–22 (Wailes and Chavez 2012).

1.2 Origin of Rice and Taxonomy

The cultivated rice belongs to the family Poaceae (Gramineae), subfamily Bambusoideae, tribe Oryzeae, and genus *Oryza*. The genus *Oryza* has been divided into four species complexes: (1) *sativa* complex, (2) *officinalis* complex, (3) *meyeriana* complex, and (4) *ridley* complex (Khush 2005). Only *Oryza sativa* complex has two cultivated species, namely, *O. sativa* and *O. glaberrima* Steud. *Oryza sativa*, the Asian rice, is grown worldwide, while *O. glaberrima* is grown on a limited acreage in a few African countries. The species in other *Oryza* complexes are wild types. The major problem with the wild types was lodging and shattering of grain and domestication selection focused on plants that had less lodging and shattering (Callaway 2014).

The two major subspecies of *O. sativa*, namely, *japonica* and *indica*, are more closely related to distinct wild varieties than they are to each other, pointing to two separate regions of domestication: *japonica* in China and *indica* in India (Gross and Zhao 2014). *Japonica* and *indica* share identical non-shatter mutations in gene sh4. However, it is suggested (Sang and Ge 2013) that the mutation arose in an ancestor of *japonica* rice first and then found its way to *indica*. In China, the domestication may have taken place in the lower end of Yangtze River Valley (Vughan et al. 2008; Fuller et al. 2009) or in the Pearl River Valley (Huang et al. 2012). It is certain that the origin of rice lies in the region of Asia covering Assam-Meghalaya area of India and river valley regions of southeast China (Swaminathan 1984; Fuller 2011). *Indicas* are grown throughout the tropics and subtropics. Traditional *indicas* are characterized by tall stature, weak stem, droopy leaves, high tillering capacity, long grains, and poor response to high nutrient input conditions. *Japonicas* have stiff, short stalk, and erect type with round grains and are highly responsive to nutrient inputs. These are limited to the temperate zones. A third subspecies, which is broad grained and thrives under tropical conditions, was identified based on morphology and initially called *javanica*, but is now known as *tropical japonica*. Examples of this subspecies include the medium grain "Tinawon" and "Unoy" cultivars, which are grown in the high-elevation rice terraces of the Cordillera Mountains of northern Luzon, Philippines. Because of high yields and economic returns, International Rice Research Institute (IRRI), Philippines, developed two cultivars of *japonica* suitable for tropics, which are NSIC Rc170 or IRRI 142 (now called MS11) and NSCIC Rc220 or IRRI 152 for large-scale cultivation in the Philippines (Kang 2010).

1.3 Area, Production, and Consumption

Although rice yields are still growing, the rate of growth has been declining; compound growth rate was 2.5 % per annum (pa) during 1962–1979 and declined to 1.4 % pa during 1980–2011 (Adjao and Staatz 2015). The cereal production forecast by Food and Agriculture Organization (FAO) in April–June 2015 indicated that out of the total cereal production of 2524.3 MMT, the contribution of rice (milled), wheat, and coarse grains is likely to be 500.5 MMT, 723.4 MMT, and 1300.3 MMT, respectively. At the global level, the share of rice in total cereal production did not change significantly between 1961 and 2007, starting from 24.6 % and gradually reaching to 28.1 % (Timmer 2010); thus, about 20 % of cereal production in the world is going to be rice.

Table 1.2 Predictions of area, production, consumption, and yield of rice

Item	2010/11	2015/16	2021/22
Area (M ha)	157.3	160.2	160.5
Production (MMT)	451.4	481.5	502.7
Consumption (MMT)	446.2	478.5	501.0
Average yield (MT ha^{-1})	2.87	3.01	3.13

Source: Wailes and Chavez (2012)
Mha million hectares, *MMT* million metric tons of milled rice, *MT* ha^{-1} metric tons of milled rice per hectare

According to world rice outlook, rice-harvested area in the year 2015–2016 is likely to be 160 million hectares (M ha), and it is not going to change much by the year 2021–2022 (Table 1.2). About 80 % of the total global area under rice is in eight Asian countries, namely, China, India, Indonesia, Bangladesh, the Philippines, Vietnam, Thailand, and Myanmar, which are not just any eight countries of over 200 countries of the United Nations; they hold 46.6 % of the world's population. Asia as a whole has 90 % of the world's rice area. Comparatively, Africa has only 8 M ha (5 %) (IRRI 2006), Latin America and the Caribbean have about 5.5 M ha (Pulver et al. 2010), and Brazil has about 2.8 M ha (Lafranco 2010). However, the growth rate in rice area during 1980–2011 has been 3.1 % pa in Africa as compared to only 0.4 % pa in Asia (Adjao and Staatz 2015). Considering the total rice production, China had the largest share of 30.1 % in 2010, which is likely to decrease to 27.3 % by 2021–2022, while India's share may slightly increase from 21.5 % in 2010 to 22.4 % in 2021–2022 (Wailes and Chavez 2012). Asia's share of world's rice production may slightly decline from 89.9 to 89.3 % over 2010–2021, while Africa's share may increase from 3.4 to 4.2 % (Wailes and Chavez 2012).

1.4 Milestones in the Development of Modern Rice Varieties

1.4.1 Indica–Japonica Crosses

As a sequel to the recommendations of the International Rice Commission (IRC) Working Group, an *indica* × *japonica* hybridization program was initiated in 1951 under the auspices of FAO, United Nations. All the countries of tropical Asia participated in the project by sending the seeds of their best *indica* varieties for crossing with japonicas at the Central Rice Research Institute (CRRI), Cuttack, India. India and Malaysia distributed early-maturing, nonseasonal commercial varieties derived from this project. In India, ADT 27, which was suitable for the early monsoonal season, replaced the earlier varieties ADT 3 and ADT 4 in the Thanjavur delta. In Malaysia, Malinja and Mahsuri had the preferred grain quality and were recommended for the irrigated areas in Wellesley province (Parthasarathy 1972). Even today, Mahsuri is widely grown in many parts of tropical Asia, where there is poor soil and poor water control in the monsoonal season (DeDatta 1981).

1.4.2 High-Yielding Fertilizer Responsive Varieties

In 1949, Dee-geo-woo-gen, a semidwarf rice variety, was crossed with Tsai-yuan-chung, a tall disease-resistant variety, and Taichung Native 1 was selected from this cross and released for cultivation in 1956. This was the first semidwarf, non-lodging, high-yielding variety which had a yield potential of 6 t ha^{-1}. Later IRRI released IR-8 (Dee-geo-woo-gen × Peta, an Indonesian variety) in 1966, which also yielded 6 t ha^{-1} or more. These high-yielding *indica* varieties spread in Southeast Asia and brought the Rice Revolution. Since then, IRRI has released a number of high-yielding varieties.

1.4.2.1 Hybrid Rice

Chinese rice breeder Yuan Longping, who is known as the father of hybrid rice, successfully transferred the male sterility gene from wild rice to create the cytoplasmic genetic male sterile (CMS) line and developed hybrid rice (Virmani et al. 1997). Hybrid rice yield is reported to be as high as 13.9 t ha^{-1} (Anonymous 2011). Hybrid rice is now grown in many South Asian countries, and in China it covers more than 50 % area under rice (FAO 2004).

1.4.2.2 Basmati Rice

Basmati is an aromatic rice variety. The earliest mention of basmati rice was done by a poet Waris Shah in his authored poetic love story Heer Ranjha in 1766 (Singh 2000; Robinson 2010). Basmati rice is famous for making pulao, a delicacy in India, Pakistan, and the Middle East and even in parts of the UK, the USA, and Canada, where large Indian and Pakistani communities reside. The aroma in basmati rice is due to a compound named 2-acetyl-1-pyrroline (Wongpornchai et al. 2003). The region for origin of basmati rice is Punjab (both in India and Pakistan), and the earliest basmati rice variety Basmati 370 was released for commercial cultivation from Rice Research Station, Kala Shah Kaku (now in Pakistan), in 1933 (Singh 2000). Since yields of traditional basmati varieties were low (1 to 2.5 t ha^{-1}) and the crop used to get lodged on heavy fertilization, plant breeders at the Indian Agricultural Research Institute, New Delhi, India, crossed traditional basmati varieties with semidwarf high-yielding varieties and developed high-yielding (4–6 t ha^{-1}) basmati varieties. The first such variety was Pusa Basmati 1. One of the most popular basmati varieties is Pusa Basmati 1121, which has a kernel length of 8.2 mm and an elongation ratio of 2.0 to 2.5 on cooking (Anonymous 2007). It was released for commercial cultivation in 2003, and by 2013 it covered 84 % of the total basmati area in Punjab, 78 % in Uttar Pradesh, 68 % in Haryana, and 38 % in Uttarakhand states. One of the latest additions is Pusa Basmati 1509. Work on the development of high-yielding varieties of basmati rice has also been conducted in Pakistan. The basmati rice varieties released in Pakistan include C-622, Basmati Pak (or Kernal

Basmati), Basmati 198, Basmati 370, Pak 177, Basmati 385, Shaheen Basmati, Basmati 2000, Super Basmati and Basmati 515, and PK-386 (Zafar 2015). Shaheen Basmati is more tolerant to salt-affected soils than other varieties, Basmati 2000 has better threshing characteristics, and Basmati 515 has a higher-yield potential than other varieties. Despite being released in 1996, Super Basmati is still widely grown in Pakistan (nearly 80–90 % of area under rice). In the USA, aromatic rice variety Texmati was developed by Rice Tec Inc., Alvin, Texas.

1.4.2.3 Genetically Modified Rice

One of the genetically modified (GM) rice is "golden rice." Golden rice has been engineered to express beta-carotene by introducing a combination of genes that code for biosynthesis pathway for the production of provitamin A in the endosperm (Ye et al. 2000). Enhancement of Fe content in rice has also been achieved by improving the uptake from soil and by increasing the absorption and storage of Fe (Murray-Kolb et al. 2002; Takahashi et al. 2001). Further, GM rice has been developed that produces both beta-carotene and ferritin (Potrykus et al. 1996). However, golden rice has been a point of controversy. There are problems in the acceptance of GM crops in several countries (Jaffe 2005).

Herbicide-resistant (HR) rice is another group among GM rice. So far three types of HR rice have been developed. Glyphosate- and glufosinate-resistant ones are GM rice, whereas imidazolinone-resistant rice was developed through chemically induced seed mutagenesis and conventional breeding (Gealy et al. 2003). HR rice are widely grown in the USA. However, there is a potential risk of transfer of the genes conferring HR traits to wild and weedy species (Kumar et al. 2008). Recently, Burgos et al. (2014) from the USA have reported that continuous growing of HR Clearfield (nontransgenic HR) rice has led to the evolution of HR weeds, which tend to possess crop halophytes in the portion of chromosome 2 containing the acetolactate synthase gene which confers herbicide resistance to Clearfield rice.

1.4.2.4 NERICA Rice

Oryza glaberrima was domesticated in Africa about 3500 years ago. It was prone to lodging and its panicles had shattering problem. To overcome these problems, *O. sativa* was introduced in Africa some 450 years ago. *Oryza sativa* gave higher yields and has spread steadily in Africa. However, some *O. glaberrima* varieties, such as CG 14, are more weed competitive and resistant to iron toxicity, drought, nematodes, waterlogging, and major African rice diseases and pests. They also adapt better to acid soils and to soils low in phosphorus (P). Efforts are therefore underway to develop crosses between *O. glaberrima* and *O. sativa* since the 1990s. These new rice types are known as NERICA (New Rice for Africa). The best NERICA varieties combine the stress tolerance of *O. glaberrima* and high-yield potential of *O. sativa* (Mohapatra, 2010).

1.4.2.5 Aerobic Rice

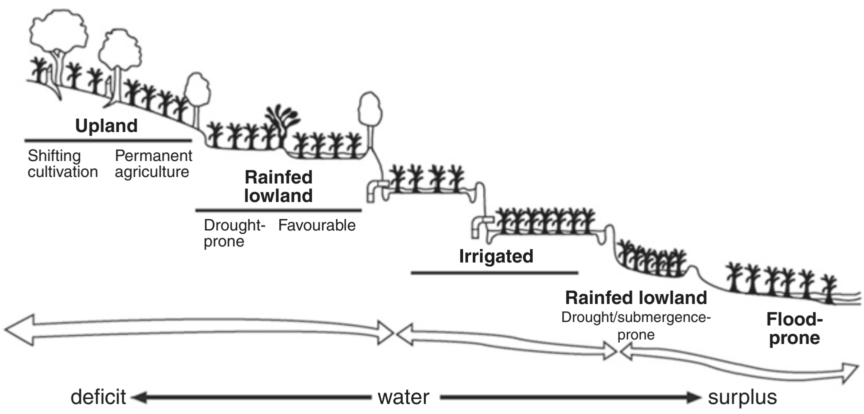
Aerobic rice varieties (ARVs) were developed to permit growing of rice as an upland crop, such as wheat (Prasad 2011). In China, the breeding program for aerobic rice was initiated in the 1980s at the China Agricultural University (CAU), the China Academy of Agricultural Sciences (CAAS), the Liaoning Province Academy of Agricultural Sciences (LPAAS), and the Dandong Academy of Agricultural Sciences (DAAS). This led to the development of Han Dao (HD)297, HD277, and HD502. In addition, LPAA released Han 58 and DAAS released Danjing 5. These new varieties have more drought tolerance, reduced plant height, higher lodging resistance, erect upper leaves, and increased resistance to blast, higher grain yield, and better grain quality. The HD277 and H58 are currently the most extensively grown ARVs in China (Huaqi et al. 2002).

In Brazil, the National Research Center for Rice and Beans has developed many ARVs. Maravilha and Primavera were the first upland rice varieties, released in 1996, that combined the grain quality and desirable aerobic rice characteristics (Pinheiro 1999). Recently released ARVs are Talento and Soberana (Pinheiro et al. 2006) and AN Cambara (Santana 2010).

IRRI initiated its own program for developing ARVs with a focus on tropical and subtropical regions and developed IR55423-01 (named Apo) and UPLRI-5 from the Philippines, B6144-MR-6-0-0 from Indonesia, and CT6510-24-1-2 from Columbia. Yields obtained with ARVs vary from 4.5 to 6.5 tha^{-1}, which is about the double or triple of that obtained with traditional upland varieties and 20–30 % less than that obtained with lowland varieties grown under flooded conditions (Farooq et al. 2009). Aerobic rice helps in doubling the water use efficiency, and there is 50 % water saving relative to the conventional lowland rice (Zhao et al. 2010).

1.5 Rice Ecosystems

Rice is grown under a wide variety of environments. The IRRI (IRRI 1993) has categorized rice field ecosystems (RFES) into four types: upland, irrigated, rainfed lowland, and flood-prone rice ecosystems (Fig. 1.1). The upland RFES varies from low-lying valleys to undulating and steep sloping land with high runoff and lateral water movement and covers less than 13 % of the world's rice land. In the irrigated RFES, the rice fields have assured water supply for one or more crops a year. Irrigated lands cover about half of the world's rice lands and produce about 75 % of the world's rice. The rainfed lowland RFES has both flooding and drought problems. About one quarter of the world's rice fields are rainfed lowlands. The remaining rice fields are classified as flood-prone RFES and cover about 8 % of the world rice area. This RFES is subjected to uncontrolled flooding. The land may remain submerged for as long as 5 months at a time with water depth from 0.5 to 4.0 m or more, and in some areas there could be even intermittent flooding with brackish



Upland	Rainfed lowland	Irrigated	Flood-prone
Level to steeply sloping fields; rarely flooded, aerobic soil; rice direct seeded on plowed dry soil or dibbled in wet, non-puddled soil	Level to slightly sloping, bunded fields; non-continuous flooding of variable depth and duration; submergence not exceeding 50 cm for more than 10 consecutive days; rice transplanted in puddle soil or direct seeded on puddle or plowed dry soil; alternating aerobic to anaerobic soil of variable frequency and duration	Leveled, bunded fields with water control; rice transplanted or direct seeded in puddle soil; shallow flooded with anaerobic soil during crop growth	Level to slightly sloping or depressed fields; more than 10 consecutive days of medium to very deep flooding (50 to more than 300 cm) during crop growth; rice transplanted in puddle soil or direct seeded on plowed dry soil; aerobic or anaerobic soil; soil salinity or toxicity in tidal areas

Fig. 1.1 Rice land ecosystems (after Greenland 1997 as adapted from IRRI 1993) (Reproduced with the kind permission from IRRI)

water caused by tidal fluctuations. These different RFESs have varying plant nutrient problems, weed species, and pest problems and demand different rice crop management strategies.

1.6 Rice Soils

The wide ranges of environmental conditions lead to an equally wide variety of rice soils. Moorman (1978) observed that the most important soil suborders on which rice is grown are Aquents, Aquepts, Orchepts, Tropepts, Aqualfs, and Aquults. As regards texture, rice is grown on loamy sands to heavy clay loams or clays. It is grown on acid soils below pH 5 to sodic soils having pH above 9. Again the rice soils may have organic matter contents of less than 1 % in loamy sands to peat soils having organic matter content as high as 95 %. Flooding changes the entire chemistry of soils. The submergence leads to gradual depletion of oxygen in the soil, and this causes reduction of a number of nutrient ions such as nitrates, sulfates, iron, manganese, etc. (Patrick and Mahapatra 1968). A number of chemical reactions follow submergence, which affect rice plant growth. Some of these are briefly discussed here.

1.6.1 Redox Potential

The single electrochemical property that serves to distinguish a submerged soil from a well-drained soil is the reduction of oxygen, which is measured by its redox potential. The low potentials (0.2 to −0.4 V) of submerged soils reflect this reduced state as a contrast to the high potentials (0.8 to 0.3 V) of aerobic soils (Ponnamperuma 1972). Iron, manganese, and sulfur availability is most affected by the changes in redox potential.

1.6.2 Soil pH

The overall effect of soil submergence is to increase the pH of acid soils and to depress the pH of sodic and calcareous soils, the ultimate result being convergence to pH 7.0 (Ponnamperuma 1972) (Fig. 1.2). This permits the rice plants to grow well on acid as well as alkaline soils too. You may consult Ponnamperuma (1972) for further information regarding the characteristics of submerged soils.

1.6.3 Iron

Under submerged conditions Fe^{3+} is reduced to Fe^{2+}. The relationship between Fe^{2+} and pH is given by the expression (Ponnamperuma 1972)

$$pFe^{2+} = 2pH - 10.8$$

According to the above expression, the activity of Fe^{2+} is likely to be 3.5 ppm at pH 7.5, 35 ppm at pH 7.0, 350 ppm at pH 6.5, and 3500 ppm at pH 6.0. Thus, a pH change of 0.5 units above or below pH 7.0 can spell the difference between deficiency and toxicity of iron in submerged soils. Iron toxicity leads to bronzing disease indicated by brown spots on the leaves, which may coalesce to cover the entire leaf (Becker and Asch 2005). This is due to accumulation of oxidized polyphenols (Dobermann and Fairhurst 2000). Such leaves contain 300 to 1000 μg Fe^{2+} g^{-1} dry matter (Ottow et al. 1983). Iron toxicity prone areas include poorly drained Acquents, Acquepts, and Acquults in Indonesia, the Philippines, and Sri Lanka

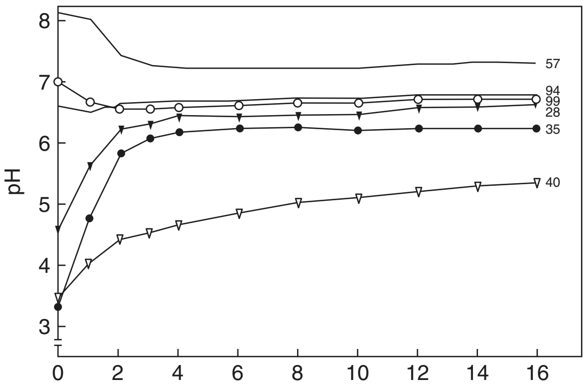


Fig. 1.2 Changes in soil pH due to submergence (numbers for different curves refer to soil sample numbers; soils were clay or clay loam having 2.2 to 7.2 % organic matter, 0.08 to 4.7 % iron, and 0.0 to 0.8 % manganese) (From: Ponnamperuma, F.N. (1972) Advances in Agronomy 24:29–96) (Reproduced with the kind permission from Elsevier Limited, Kidlington, Oxford, UK)

(Jagsujinda and Patrick 1993); acid sulfate and peat soils of Brundi, Senegl, and Madagascar (Genon et al. 1994); lowlands of Western Africa (Audebert et al. 2006); and flooded soils of Assam and northeast region of India (Singh et al. 2003). Drainage and liming help in overcoming iron deficiency (Prasad 2000).

1.6.4 Manganese

Reduced conditions in submerged rice fields also lead to reduction of Mn^{4+} to Mn^{2+}. In the soils which are rich in manganese and organic carbon, Mn^{2+} concentration can go as high as 90 ppm within a week or two after submergence followed by subsequent decline to a stable level of 10 ppm (Ponnamperuma 1972). This leads to manganese toxicity in rice, which generally occurs in concurrence with iron deficiency (Prasad 2007). Potassium (K) fertilization (Alam et al. 2003) and Si application (Li et al. 2012) can ameliorate manganese deficiency in rice.

1.6.5 Sulfur

Under submergence, sulfate is reduced to sulfide (S^{2-}), and in iron-deficient soils, H_2S (hydrogen sulfide) is produced, which is toxic to rice (Tanaka et al. 1968; Joshi et al. 1975; Armstrong and Armstrong 2005). It damages rice roots, which become sparse, have reduced laterals, and turn black, and the disease is known as “Akiochi” in Japan. Hydrogen sulfide production under submerged conditions adversely affects not only rice but also acts as a host of other plant species and organisms (Lamers et al. 2013). When sufficient iron is present, FeS is formed and gets precipitated. Submergence can therefore lead to sulfur deficiency in rice (Yamaguchi 1999).

Effects of submergence on N, P, K, and Zn are discussed under nutrient management.

1.7 Cropping Systems (CS)

In tropical regions, one, two, or three crops of rice are taken depending upon the rainfall and availability of irrigation water. In subtropical, subtemperate, and temperate regions, upland crops, such as beans, corn, wheat, and vegetables, are grown before or after rice. Beans and fodder legumes, such as clovers, and legume green manures such as *Sesbania aculeata* improve soil fertility (George and Prasad 1989; John et al. 1989; Sharma and Prasad 1999). Of great interest is the rice–wheat (*Triticum aestivum*) cropping system (RWCS) practiced over 18.5 million hectares in South Asia and Southeast Asia (Prasad 2005; Ladha et al. 2009). In the Indian subcontinent, rice is grown during rainy season (July to November) when 700–1000 mm rainfall is received, while wheat is grown during the winter season (November to May) on stored soil moisture with supportive irrigation. In China, rice and wheat have several common months, and quite a bit of rain is received during the wheat growing season. Many farmers in India and Pakistan take a third crop of potato (*Solanum tuberosum*) or toria (*Brassica campestris*) in between rice and wheat. Also, many farmers cultivate mung bean (*Vigna radiata*)/cowpea (*Vigna unguiculata*)/green manure in between wheat and rice. Some of the rice-based cropping systems are rice–wheat, rice–potato–wheat, rice–toria–wheat, rice–wheat–mung bean, rice–wheat–cowpea, rice–wheat–green manure (*Sesbania* spp., *Crotalaria* spp.), rice–potato–wheat–green manure, rice–wheat–sunflower (*Helianthus annuus*), rice–wheat–rice, rice–vegetable peas (*Pisum sativum*)–wheat, rice–vegetable peas–wheat–green manure, and rice–wheat–maize (*Zea mays*). There could be many more variants involving vegetables and other short-duration crops.

The major problem of the RWCS is that rice is transplanted on a puddled soil in the rice production system called “conventional tillage with typical puddled transplanted rice” (CTTPR), which has to be dried and given primary tillage for a soft seedbed for wheat. This delays seeding of wheat resulting in serious yield losses. Also repeated puddling adversely affects soil physical properties by destroying soil aggregates, reducing permeability in subsurface layers, and forming hardpans at shallow depths (Sharma et al. 2003, 2004), all of which can negatively affect the following wheat crop (Tripathi et al. 2005). To avoid the delay in sowing wheat, no-till direct seeding technology has been developed, which has been very successful (Kumar and Ladha 2011).

1.8 Constraints to Sustained Rice Production

The productivity and sustainability of rice and rice-based systems are threatened because of (1) increasing scarcity of resources (land, water, and labor and machines), (2) inefficient use of inputs (fertilizer, water, herbicides, insecticides, etc.), and (3) the rising cost of cultivation.

1.8.1 Natural Resources

1.8.1.1 Land

Rice farm holdings in Asia are quite small, and arable land available per person is already too little compared to developed countries like the USA (Table 1.3). Further, more and more land is being diverted to roads, railways, and dwellings indicating a decline in arable land. Thus, the only hope for continued sustainable rice production is in increasing productivity per hectare.

1.8.1.2 Water

Rice growers in Asia are small holder farmers who are always on the mercy of nature. Tuong and Bouman (2003) reported that seasonal water input for TPR varies from 660 to 5280 mm depending on growing season, climatic conditions, soil type, and hydrological conditions. This consists of (1) 160–1580 mm for land preparation (puddling), 400–700 mm for evapotranspiration (ET), and 1500–3000 mm (for loamy/sandy soils) or 100–500 mm (for heavy soils) of unavoidable losses due to percolation and seepage. Gupta et al. (2002) estimated that water use for rice in the Indo-Gangetic Plains varied from 1144 mm in Bihar (wetter region) to 1560 mm in Haryana (drier region). In the Philippines, water use has been reported as 790–1430 mm (aerobic fields) or 1240–1880 mm (flooded fields) (Bouman et al. 2005). In Pakistan, water input was 2190–2445 mm for flooded rice, 1793–1935 mm for alternate wetting and drying, and 1573–1635 mm for direct-seeded rice (Jabran et al. 2015a, b). The higher water application in rice as compared to other cereals is mostly due to water requirements for puddling and losses associated with continuous flooding such as seepage and deep percolation losses to groundwater (Hafeez et al. 2007). Seepage and percolation losses vary from 25 % to 85 % of total water input depending on soil type and water table and 25–50 % in heavy soils with shallow water tables and 50–85 % in coarse-textured soil.

Total seasonal water input to rice fields varies from as little as 400 mm in heavy clay soils with shallow groundwater tables to more than 2000 mm in coarse-textured (sandy or loamy) soils with deep groundwater tables. Thus, on average about 1300–1500 mm of water is needed for irrigated rice in Asia. On an average, it takes 1432

Table 1.3 Arable land (ha person^{-1}) in Asian countries as compared to that in the USA

Country	2000–2004	2010–2014
Bangladesh	0.05	0.05
Cambodia	0.28	0.028
China	0.08	0.08
India	0.13	0.13
Indonesia	0.10	0.10
Japan	0.03	0.03
Korea, Democratic Republic	0.09	0.09
Korea Republic	0.03	0.03
Malaysia	0.06	0.03
Myanmar	0.21	0.20
Nepal	0.09	0.08
Pakistan	0.12	0.12
Philippines	0.06	0.06
Sri Lanka	0.06	0.06
Vietnam	0.07	0.07
USA	0.52	0.49

Source: World Bank-IDA (2015) (via the Internet)

liters of water to produce 1 kg of rice in an irrigated lowland production system (http://www.knowledgebank.irri.org/step-by-step-production/growth/water-management).

Irrigated rice receives an estimated 34–43 % of the total world's irrigation water or about 24–30 % of the entire world's developed freshwater resources (RKB 2015). Due to increase in area under irrigated rice, the use of groundwater structures (mostly irrigation pumps) and use of groundwater in Asia have considerably increased (Table 1.4). Thus, irrigated rice has resulted in lowering the water table, and in some regions this has reached an alarming situation. For example, in North China Plain (NCP), water table is declining by 1–3 m each year (Shah et al. 2000), while in the Indo-Gangetic Plain (IGP) of India, it is declining by 0.5–0.7 m each year (Carriger and Vallee 2007; Tuong and Bouman 2003).

Increasing water scarcity has threatened the productivity and sustainability of the irrigated rice system in Asia (Tuong et al. 2004). Irrigation water is becoming scarce each day, and according to World Economic Forum (WEF 2011) of UNEP, several rice-growing Asian countries are likely to face 20–40 % (average 30 %) shortage in water availability by 2025 (Fig. 1.3).

In response to water shortage, researchers have made efforts to grow rice with less water inputs. These include the technologies such as alternate wetting and drying, aerobic rice cultivation, dry direct-seeded rice, and rice cultivation using drip irrigation. For details, please see the chapter "Rice Production Methods."

Table 1.4 Number of groundwater structures (mostly irrigation pumps) and annual groundwater use

Country	Groundwater structures (million)	Groundwater use (km^3 $yr.^{-1}$)
Bangladesh	0.80	31
India	19	150
Nepal Terai	0.06	<1
Pakistan (Punjab province)	45	45
China	3.5	75
Iran	0.5	29
Mexico	0.07	29
USA	0.2	100

Source: Shah (2005, 2007)

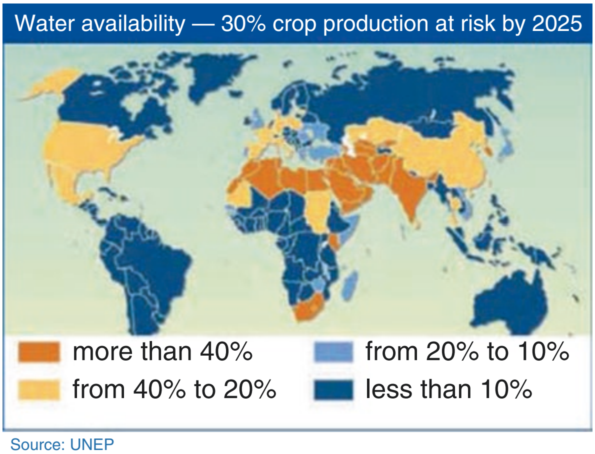


Fig. 1.3 Water shortage in different parts of the world (Reproduced with the kind permission from UNEP)

1.8.1.3 Labor

In Asia, where most rice cultivation operations such as nursery raising, transplanting, weeding, and even harvesting are still done manually, the labor requirements are very high for CTTPR and are reported to be 237 person-days ha^{-1} in Malaysia (Wong and Moorka 1996), 229 person-days ha^{-1} in India (Thakur et al. 2004), and 139 person-days ha^{-1} in Bangladesh (Rahman et al. (2008). Labor availability for agriculture is declining globally, and rice, which is a very labor-intensive crop, is going to suffer the most. Worldwide 60 % of all child labor in the age group of 5 to 17 works in agriculture including farming, fisheries, aquaculture, forestry, and livestock, mostly as unpaid family members (ILO 2010). Further, wages for farm workers in South and Southeast Asia have increased; the average wage in the 2010s is five times higher than that in the 1970s, and an increase of 100 to 200 % in the current labor wages is a realistic expectation within the next 5–10 years

(Beltran et al. 2012). The mass rural-to-urban movement of young working class and resulting high wages of farm labor will eventually lead to mechanization of rice cultivation in Asia.

1.8.2 Inputs

1.8.2.1 Energy: Mechanization of Rice Cultivation

Energy is required for all field operations in rice culture. The major advantage with machines is precision and saving of time. For each ton of rice produced, more than 7000 mega joules (MJ) of energy are needed, whether provided by humans, animals, or machines (Rickman 2012). For instance, manual plowing of a hectare requires 150 person-days, 12 days when animals are used, a day with a two-wheel tractor, and only 1–2 hours with a four-wheel tractor; the same amount of energy of about 1500 mega joules is required to do the job. The major difference is the time saved (Rickman 2012). Similar is the situation with transplanting. In one study, the mechanical transplanting of rice proved beneficial in saving of 66 % cost of transplanting and required only 7 % of time as compared with manual transplanting (Sharma et al. 2002a, b). Moreover, it is seen that population of the plants in the farmers' field is generally low (18–20 plants m^{-2}) because the hired labor tends to transplant more area in a limited time for higher earnings, but it results in reduced grain yields. Aggarwal and Singh (2015) opined that mechanical transplanting is a promising solution to avoid yield reduction, as it helps in avoiding delay in transplanting under labor-scarce conditions particularly in Indo-Gangetic plains. Similarly, the cost of rice cultivation by drum seeding was reduced by 26 % because of mechanized paddy cultivation, and net return per acre also increased by 34 % (Malleswara Rao et al. 2014). As regards harvesting, manual harvesting and threshing cost $100–120 per hectare, while manual harvesting with mechanical threshing costs about $80 per hectare, which is similar to combine harvesting that costs $80–100 per hectare (Rickman 2012). Moreover, grain losses due to shattering are much less from rice combine harvesters compared with the manual harvesting. Rice combine harvesters are expensive and relatively sophisticated machines. Small holder farmers obviously cannot afford to buy or maintain these machines. Availability of combine harvesters and other farm machinery on custom-hiring basis is the only solution and is already being practiced in some countries.

In countries like the USA, Brazil, and Japan, rice cultivation is completely mechanized, while in developing countries it is fully manual or partially mechanized. The majority of US rice is typically planted with seed drills after preparatory cultivation involving several tillage and smoothing operations and basal fertilizer application. After or before seeding, levees are established using levee disks or squeezers, and gates and spills are established using vinyl and/or metal frames to permit maintenance of shallow 5–10 cm standing water throughout the growing season, and the fields are drained 15–25 days after heading (Synder and Slaton 2001). In Sacramento Valley in California, rice seeding is done by airplanes in standing water (Souza 2005). Using GPS (global positioning system) equipment, pilots are able to lay the seed exactly on target. Fertilizer and pesticide application all over the USA is done by airplanes, and harvesting is done by combine harvesters. In Brazil, all operations are done using tractor and other necessary equipment, while harvesting is done by combine harvesters (Fageria et al. 2014). In Japan, paddy rice production has been mechanized since the 1970s, and 90 % of rice transplanting is mechanized (Li et al. 2005). Also in South Korea, 100 % of the tillage, 98 % of the transplanting, 100 % of the spraying, and 99 % of the harvesting of paddy rice production have been mechanized (Park and Kim 2005). In Japan, again most operations are done by especially designed equipment including transplanters, hand-operated harvesters, or combine harvesters (Oshino 1985). In China, mechanization of rice cultivation is in progress (Xu et al. 2011).

1.8.2.2 Fertilizer

Nitrogen

Rice crop uses about 21–25 % of the total N fertilizer consumed globally. However, the N use efficiency in rice is very low. Agronomic efficiency of N in rice was reported to be 13 kg grain kg^{-1} N from India (Prasad et al. 2000) and 10.4 kg grain kg^{-1} N from China (Zhang et al. 2007a). The low nitrogen use efficiency in rice and even in other crops is due to four N loss mechanisms, namely, surface runoff on sloping lands, ammonia volatilization, leaching, and denitrification (Zou et al. 2005; Towprayoon et al. 2005; Pathak et al. 2006; Ussiri and Lal 2012; Prasad et al. 2014; Prasad and Shivay 2015). The agronomic techniques employed to reduce these losses include deep placement and split application of N supported by balanced and adequate application of other nutrients to boost crop growth (Prasad 2013). Another approach has been the use of nitrification inhibitors (Prasad and Power 1995), urease inhibitors (Kiss and Simihian 2002), and slow-release N fertilizers (Prasad et al. 1971; Trenkel 1997; Shaviv 2001). These materials have met with mixed success. The government of India has decided to coat all urea manufactured or imported in the country with neem (*Azadirachta indica* Juss) (Prasad and Shivay 2015). Neem-coated urea was developed by Prasad et al. (1994, 2007) at the Indian Agricultural Research Institute, New Delhi, and is based on the mild nitrification-inhibiting properties of neem (Reddy and Prasad 1975).

Phosphorus

As a contrast to N, which is available in infinite amounts in the atmosphere, P fertilizers are made from phosphate rocks, which are a nonrenewable resource and are sufficient only for 1000 years or less, depending upon the processes used for their extraction and manufacture and the methods of their use on agricultural fields (Smil 2002; Zhang et al. 2008). The global estimates of phosphate rock are at 67,000 billon metric tons (BMT), and in Asia, only China has sizeable phosphate rock deposits (3700 BMT) (van Kauwenbergh et al. 2013).

Although recovery efficiency of P by rice is about 15–30 %, the rest of P gets fixed in soil (Sample et al. 1986). Submergence of rice fields leads to a flush of available P in soil (Kirk et al. 1990); however, continued submergence can reverse this effect as P is precipitated in the oxidized rhizosphere and sorbed on the solid phases during reduction (Patrick and Mahapatra 1968). A well-planned integrated P management using organic manures, crop residues, and P-solubilizing microorganisms is therefore important (Blaise et al. 2014). In the RWCS, drying during wheat season reduces P availability (Kumar and Yadav 2001). Good response to P application has been reported from India (Prasad 2007; Singh et al. 2014), China (Zhu et al. 2007; Bi et al. 2014; Guan et al. 2014), and Brazil (Fageria et al. 2014). Adequate P fertilization of rice is therefore necessary for sustained good yields of rice.

Potassium

Like P, K minerals are also a nonrenewable resource. The global deposits are estimated at 250 billion metric tons (BMT) (USGS 2008) with Canada having the largest deposits, followed by Russia. In Asia, only China has sizeable K mineral deposits, and in 2014/2015, it produced 5 MMT of potash fertilizers against its consumption of over 9 MMT (Tan 2015). Response of rice to K in China is much higher than in India. Zhang et al. (2010) observed that addition of 100 kg ha^{-1} to each rice crop in rice–rice rotation was not enough to maintain initial K availability in soil. Red and lateritic kaolinitic soils have less total K and non-exchangeable K than calcareous illitic and vertic smectitic soils and are therefore likely to need more K fertilization in rice (Sekhon et al. 1992). This would explain why response of rice to K fertilizers was more (9.7 kg grainkg^{-1} K) in Western Ghats and Karnataka Plateau having red and lateritic soil than in north Indian alluvial plains having calcareous illitic soils (Tandon and Sekhon 1988). Tiwari (2014) estimated that a harvest of 200 MMT of food grains per year will lead to a deficit of 5.8 million metric tons of K from the soil, which has to be replenished. Thus, adequate K fertilization of rice is important.

Zinc

Nene (1966) was the first to report that *Khaira* disease of rice (brown/maroon coloring of leaves) that was due to zinc (Zn) deficiency. Good response of rice to zinc fertilization is reported from all over the world (Alloway 2008). Further, Zn deficiency in soils is also linked with low Zn concentrations in grains of cereals including rice. Therefore, efforts are underway to develop GM rice with grains having higher concentration of Zn (Stein 2010) as well toward agronomic biofortification of rice with Zn (Prasad et al. 2014).

1.8.2.3 Pesticides

It is estimated that about 120–200 MMT of rice grain is lost in tropical Asia due to insects, diseases, and weeds (Gianessi 2014). Conventional rice-growing regions are humid to subhumid, and there are a large number of diseases such as blast, brown leaf spot, sheath blight, bacterial blight, tungro virus, and grassy stunt virus (Hollier et al. 1993). Blast epidemics in Malaysia and the Philippines caused a 50–70 % yield reduction (Gianessi 2014). Similarly, the damage due to sheath blight caused a loss of 17–25 % in Malaysia (Banniza and Holderness 2001), 10 % in India, and 20 % in Thailand (Boukaew and Prasertan 2014). It is difficult to breed rice varieties with high genetic resistance to these diseases; however, the development of multiple resistances for diseases and insect pests is the only solution to the problem (Singh et al. 2012; Suh et al. 2013). Details have been discussed in the chapter "Disease Management in Rice."

Similarly, there are a large number of insect pests that attack the rice crop. Some important ones are brown plant hopper, white-backed plant hopper, green leaf hopper, rice mealy bug, rice aphid, rice leaf folder, rice swarming caterpillar, rice gall midge, and rice gundhi bug (Pathak and Khan 1994). Stem borers alone can cause yield losses up to 70 % in an epidemic year (Rahim et al. 1992). Insecticide sale in South and Southeast Asia increased from US$ 409 million in 2009 to US$ 674 million in 2012 (Gianessi 2014). Current emphasis is on integrated pest management (IPM) (Oudejans 1999). Details have been discussed in the chapter "Insect Pest Management in Rice."

Weed management using herbicides has become an integral part of modern crop production including rice. Herbicides offer great flexibility of operations, are effective, and are often cost effective as compared to any other method of weed management (Chauhan et al. 2012). In rice, weeds can cause 28–74 % loss in yield (Chauhan 2012). Nevertheless, injudicious and continuous use of a single herbicide over a long period of time may result in the evolution of resistant biotype*s* and a shift in the weed flora. For example, spread of herbicide-resistant weedy rice (red rice, *Oryza sativa* L.) has been reported from Italy (Busconi et al. 2012). California rice farmers are already facing the challenge of managing herbicide-resistant weeds (Lindquist et al. 2011). A large list of biotypes showing resistance to herbicides in the USA is available (Vencill et al. 2012). Details have been discussed in the chapter "Weed Management in Rice."

1.8.3 Global Warming (GW) and Rice Production

Global warming (GW) in relation to rice cultivation has to be viewed from two angles: (1) impact of GW on future rice production and (2) contribution of rice cultivation to GW.

1.8.3.1 Impact of Global Warming on Rice Production

In a simulation study, a 2◦C increase in temperature brought about a 3–10 % decrease in grain/seed yield of rainy season crops, such as rice, groundnut (*Arachis hypogaea* L.), and soybean (*Glycine max* L.), and a 29 % decrease in grain yield of winter crops such as wheat (Prabhjyot-Kaur and Hundal 2006). In addition to the direct effects of climate change on rice plants, Chauhan and Johnson (2010a, b, c) and Chauhan et al. (2014) pointed out that increased weed growth and changed weed flora could adversely affect rice growth and production. Many weeds are C_4 plants and have a competitive advantage over rice, a C_3 plant (Yin and Struik 2008).

There are two major abiotic stresses that can affect rice production, namely, drought and salinity. Analysis of models based on soil moisture changes, drought indices, and precipitation minus evaporation suggests increased risk of drought in the next 30–90 years over many land areas either by decreased precipitation or increased evaporation (Dai 2013). However, Trenbath et al. (2014) observed that increased heating due to global warming may cause droughts to set in earlier than predicted. Wassman et al. (2009) observed that current temperatures are already approaching critical levels during the susceptible stages of the rice plant in Pakistan/north India (during October), south India (during April, August), east India/Bangladesh/Myanmar/Thailand/Laos/Cambodia (during March–June), Vietnam (April/August), the Philippines (April/June), Indonesia (August), and China (during July/August) and drought stress is expected to affect rice growth and production. Wassmann and Dobermann (2007) observed that increasing temperatures or hotter night temperatures can cause increased spikelet sterility and reduce grain yield in rice.

Intergovernmental Panel on Climate Change (IPCC 2001) predicted that between 1990 and 2100, sea level may rise by 9–88 cm in different regions of the world. This will affect rice production in mega-deltas in Vietnam, Myanmar, and Bangladesh (Wassmann et al. 2009). The other hot spot with especially high climate change risk is the Indo-Gangetic Plains (the rice–wheat copping system belt), which will be affected by the melting of the Himalayan glaciers (Wassmann et al. 2009). Developing rice production systems and production technology with higher resilience to flooding and salinity is the key for maintaining sustained rice production in these areas.

1.8.3.2 Contribution of Rice Cultivation to Global Warming

Under submerged rice paddy conditions, methane (CH_4) is produced due to anaerobic conditions, while nitrous oxide (N_2O) is produced due to nitrification–denitrification processes from the applied fertilizer N both under aerobic upland and anaerobic lowland conditions. Both these gases contribute to GW. The global warming potential (GWP) of methane is 72 times that of carbon dioxide (CO_2) (which is taken as 1.0) for a life span of 12 years. According to Sass et al. (1999), CH_4 emission is 13–17 Tg y^{-1} from China (Wang et al. 1994), 2.4–6.0 Tg y^{-1} from India (Parashar et al. 1994), 0.04–8.77 Tg y^{-1} from Japan (Yagi et al. 1994), 0.31–7.0 Tg y^{-1} from the Philippines (Neue and Saas 1994), and 0.328 Tg y^{-1} from the USA (Leip and Bocchi 2007). Of the total methane emission from a country, rice contributes about 1.3 % in the USA, 3.7 % in Italy, 24 % in Japan, 30 % in China, and 35 % in India (Leip and Bocchi 2007).

Total CH_4 emission from the world is anticipated at 16–34 Tg y^{-1} and is considered to be 63 % of total anthropogenic CH_4 emission in the world (Saas et al. 1994). However, IPCC (1996) estimated that the contribution of rice cultivation toward total global methane emission is 5–20 %. Addition of rice straw to rice fields increases CH_4 emission (Sass et al. 1990; Rath et al. 1999). Midterm drainage during rice-growing period or alternate wetting and drying can substantially reduce CH_4 emission from rice fields, but it increases N_2O emission (Sanders et al. 2014; Pandey et al. 2014). Methane production is negligible under non-flooded aerobic conditions (Ramakrishna et al. 1995). However, there are uncertainties in estimating methane emission, and recently, Tian et al. (2015) using process-based couple biogeochemical model estimated total methane CH_4 from global terrestrial ecosystems during 1981–2010 at 144.39 ±12.90 Tg C y^{-1}; annual increasing trend was 0.43±0.06 Tg C y^{-1}. The most rapid increase in methane emission during 1981–2010 was found in natural wetlands and rice fields due to increased cultivation area and climate warming (Tian et al. 2015). Sanders et al. (2014) observed that in rice fields CH_4 contributed about 90 % of the total GWP.

The GWP of N_2O is 289 times that of CO_2 and its life span is 114 years. Thus its potential for GW is much higher than CH_4. However, the amounts of its emission are much smaller than CH_4. Tian et al. (2015) predicted global N_2O emission at 12.52 ± 0.74 Tg N y^{-1}, while Davidson and Kanter (2014) estimated it to be between 10 and 12 Tg N y^{-1}. Net anthropogenic N_2O emission is estimated at 5.3 Tg Ny^{-1}, out of which 66 % is predicted from agriculture and business-as-usual emission scenarios project almost doubling of N_2O emissions by 2050 (Davidson and Kanter 2014). The largest increase in N_2O emission during 1981–2010 occurred in upland crops due to increasing air temperature and N fertilizer use (Tian et al. 2015).

1.9 Rice Cultivation and Environmental Pollution

Fertilizers applied to rice contribute considerably toward environmental pollution. Only about one-third of the N fertilizer applied is taken up by the rice crop, while the rest two-thirds, except for a small fraction being immobilized by the soil organisms, is lost through ammonia volatilization, denitrification, and leaching and surface runoff; estimates for these losses are at 4.1 Tg, 3.1 Tg, and 3.1 Tg, respectively (Pathak 2013). While ammonia produced by volatilization and nitrous oxide produced by denitrification are lost to the atmosphere, nitrates are leached down the profile or move with surface runoff (Prasad and Shivay 2014) and are responsible for eutrophication of surface (lakes and estuaries) and groundwater. Similarly the recovery efficiency of P fertilizer applied to rice is only 15–30 %.

1.9.1 Eutrophication of Surface and Groundwater

An important current issue is the need to reduce anthropogenic nutrient inputs to aquatic ecosystems in order to protect drinking water supplies and to reduce eutrophication of lakes and estuaries including the proliferation of "algal blooms" and "dead zones" in coastal marine ecosystems (Conley et al. 2009). Algal blooms lead to the depletion of dissolved oxygen in water (hypoxia), which can lead to fish mortality, and their decomposition impairs such waters for drinking, recreation, and industry (Foy 2005). Since Schindler (1974) established that P was the primary limiting nutrient for algal growth, national water policy in the USA, Canada, and Europe during the 1970s focused on P control in the lakes; however, in the last two decades, it has emerged that N is the main pollutant in the estuaries (Howarth and Marino 2006). Elevated levels of N and P have been reported from the three major lakes (Taihu, Chaohu, Dianchi) in China (Gao and Zhang 2010). Also there has been a threefold increase in nitrate concentration in the estuary of Yangtze River during the last 40 years, from 1.3 mg L^{-1} in the 1980s to 5.0 mg L^{-1} in 1999–2004 (Duan et al. 2000), and a 30 % increase in phosphate concentration during the same period from 0.056 mg L^{-1} in the 1980s to 0.73 mg L^{-1} in 1999–2004 (Zhou et al. 2008). Jin (1995) reported that up to 35 % of N and 68 % of P in surveyed lakes was from agricultural runoff. A good correlation between N concentration in river waters and N fertilizer applied in the catchment areas has been recorded (Chen et al. 2000). Duan et al. (2005) and Liu et al. (2007) observed that the risk of P loss from agricultural land is increasing. In Southern China, the leaching loss from rice fields varied from 6.7 to 27.0 kg N^{-1}, while that from runoff varied from 2.5 to 19.0 kg N ha^{-1} (Sun et al. 2003). Xia et al. (2008) reported that in rice, application of 0, 25, 60, 120, and 240 kg P ha^{-1} resulted in a loss of 0.13, 0.50, 0.94, 3.02, and 5.97 kg P ha^{-1}; thus, losses were proportionally higher as the rate of application increased. Further Zhang et al. (2007b) reported that losses were most within 1–2 months of application.

Due to nitrate leaching from agricultural fields, over half of the groundwater samples in Northern China revealed nitrate concentration higher than 50 mg L^{-1}, the World Health Organization (WHO) recommended safe level; even nitrate concentration higher than 300 mg L^{-1} was recorded in several samples (Dong et al. 2005). The situation in India is not that bad, and in studies in the rice–wheat cropping system belt in Punjab (Bharadwaj et al. 2012) as well as in the rice–rice cropping system region in Nalgonda district in Andhra Pradesh (Karthikeyan et al. 2012), about 72 % of samples of groundwater analyzed had less than 50 mg nitrate L^{-1}, and water was safe for drinking. This is because general rates of N and P application in

China are 150–200 kg N and 22–30 kg P ha^{-1} (Jin et al. 2002), while those in India are only 86–163 kg N and 4.4–25.8 kg P ha^{-1} (Sharma et al. 2010). However, in China efforts are being made to determine ecologically optimum rather than the conventional economic optimum rates of N for rice (Xia and Yan 2012). This would lead to reduced N application in rice.

1.9.2 Depletion of Ozone Layer

Ozone in the stratosphere of the earth's atmosphere works as a bio-protective filter against ultraviolet (UV) radiation, which can cause skin cancer (Narayanan et al. 2010) and cataract in eyes (Roberts 2011) of the humans. Ultraviolet radiation is also reported to adversely affect plant growth (Hollosy 2002; Zuk-Golaszewska et al. 2003). Nitrous oxide (N_2O) is a major cause of ozone layer depletion (Ravishankara et al. 2009), and about two-thirds of N_2O is produced by nitrification–denitrification reactions in agricultural fields from the applied fertilizer N (Zumft 1997; Lassey and Harvey 2007; Thomson et al. 2011). Rice cultivation due to changes in redox potential caused by submergence has therefore a role in the destruction of ozone layer in the stratosphere.

1.10 Summary and Conclusions

Rice is the staple food for nearly half of the world's population which makes it a crop of focus. As rice is grown on a variety of soils under diverse ecological conditions in all the six inhabited continents of the world, hence diverse and site-specific production technologies are required rather than a single production technology. Compared with the past (1962–1979; rice yield growth rate 2.5 %), the growth rate of rice yields per annum has been declined (1980–2011; rice yield growth rate 1.4 %).

Natural resources, land, water, and labor are becoming scarcer worldwide, and rice is going to suffer the most, because with the present production technologies, its water and labor requirements are the highest among field crops. In this backdrop, the rice production technologies with lower labor and water input hold significance. Growing rice under water-saving production systems and adoption of mechanization in developing countries are important in this regard. However, practical and social constraints in the way of such developments are desired to be resolved using current knowledge, research, and available resources. For example, weed infestation is an important issue of aerobic rice cultivation, while high financial requirement is a constraint in the installment of drip irrigation infrastructures in the rice production systems. Such issues are desired to be resolved for sustainable rice production. Other salient research issues in the rice production include the development of site-specific integrated nutrient management plans, addressing the environmental problems resulting from the overuse of N, and the development of integrated pest management plan.

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