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Rice Production Guidelines: Best Farm Management Practices and the Role of Isotopic Techniques

Joint FAO/IAEA Programme
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RICE PRODUCTION GUIDELINES: BEST FARM MANAGEMENT PRACTICES AND THE ROLE OF ISOTOPIC TECHNIQUES

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RICE PRODUCTION GUIDELINES: BEST FARM MANAGEMENT PRACTICES AND THE ROLE OF ISOTOPIC TECHNIQUES

PREPARED BY THE
JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

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FOREWORD

Rice is closely linked to the culture, food security, employment and livelihoods of the Asian population and their environment. About 90% of the global rice crop is both produced and consumed in Asia. The total harvested area in 2014 was 145 million hectares, which produced 667 million tonnes of unhusked rough rice. Major rice producers, such as China, India, Indonesia, Bangladesh, Viet Nam, Thailand, Myanmar and the Philippines produce 98.4% of Asian rice. The average annual yield across all of Asia was 4.65 tonnes per hectare in 2014, and the majority of rice farmers are small holders, with farms averaging 0.5 hectares.

Rice cultivation is already practiced intensively in many Asian countries. With the Asian population projected to increase to 5.5 billion by 2050, a further intensification of rice cultivation will be necessary if food security is to be assured. This is a daunting task given the limited or declining land and water resources, the expected rising costs of labour, energy and other inputs, and the mounting environmental problems of intensive farming in a changing climate. However, improved rice cultivation practices have been developed and used in different Asian countries. Many of these practices can be shared to improve rice productivity.

This publication is in response to a special request from IAEA technical cooperation counterparts in Asia who have been working together on projects to enhance rice production. It provides information on the best management practices and the role of isotopic techniques to quantify nitrogen use efficiency and better understand the pathways of greenhouse gas emissions. This publication presents improved rice varieties and sustainable cultivation practices from a wide range of Asian countries. These best practices will help farmers in countries with low rice yields to improve the productivity and profitability of their rice crops through the adoption of locally adapted, ‘best’ rice varieties, together with the best farm management practices. It will enable national R&D staff to select and test these varieties and practices on farmers’ fields to promote improved rice varieties and crop management practices. The IAEA officer responsible for this publication was M. Zaman of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

CONTENTS

SUMMARY

Rice has been the life-line of Asia since its domestication about 10000 years ago. Close to 90% of the world's rice is produced and consumed in Asia. The modernization of rice farming in Asia is critical to ensuring an adequate supply of rice for both current and future rice consumers. The greatest challenges to agricultural scientists will be how to intensify the production of rice without harming the environment, while at the same time adapting farming systems to both a changing climate and dwindling land and water resources.

The Rice Production Guidelines are prepared on a special request from IAEA Technical Cooperation counterparts in Asia to enhance rice production. They provide information on the best farm management practices and the role of isotopic techniques to better understand nutrient use efficiency. These Rice Production Guidelines for Asia attempt to serve the different Asian countries by bringing together a concise information package on 'improved' technologies on rice production and post-harvest procedures which have been developed during the past five decades by the International Rice Research Institute (IRRI) Philippines in close collaboration with the different Asian national research and development institutes. These Guidelines are also intended to assist farmers in learning how to adapt the new 'climate smart' rice practices to production and post-harvest technologies that are most suited to their own circumstances in the various regions and countries of Asia.

The Rice Production Guidelines emphasise the importance of initially using high quality seed for uniform crop establishment. Specific directions are provided on how farmers can best develop 'nurseries' for raising rice seedlings for transplanting, and how to prepare the main field prior to transplanting young rice seedlings. The Guidelines also describe the sowing of dry or pre-sprouted seeds and the transplanting of young rice seedlings relative to the direct seeding of dry or pre-sprouted rice seeds directly onto the main field.

The Rice Production Guidelines detail the regular and timely application of nutrients at different growth stages. They also emphasise that irrigation is critical for obtaining high yields of rice grain in irrigated lowland fields, to ensure there is no water deficit from the stage of panicle initiation to grain filling. For rainfed lowlands a better management of the variable rainfall is a major objective, one which can often be accomplished by rainwater harvesting and storage of excess rainfall in farm ponds. Additionally, by the skillful management of floods through proper drainage, a guided direction of excess rainwater to farm or community ponds, check dams may be possible.

An integrated soil and crop need-based nutrient, weed, insect pest and disease management is covered fully in the Rice Production Guidelines. By using these improved crop management methods, farmers can optimise crop yields, minimise production costs, and protect the environment. The Rice Production Guidelines also note that a timely harvest and proper post-harvest processing will minimise grain losses and maximise market value of rice grains and other rice products. Finally, the Guidelines describe isotopic technique of ^{15}N that the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture is using to develop climate-smart agricultural practices to assist farmers in Member States to find integrated solutions to increase crop productivity through better use nutrients.

1. INTRODUCTION

Rice is the main staple food for half of the world's population, 90% of which reside in Asia. Rice cultivation is believed to have originated at approximately the same time in each of the eastern region of India more than 10000 years ago and also in the Yangtze valley of what is now the People's Republic of China some 8200–13500 years ago [1, 2]. Rice is also closely linked to our human cultural heritage, as many traditional festivals and cultural practices are associated with rice farming, specifically the harvesting of rice crops. Currently, rice farming utilises 135 mha and directly employs more than 300 million people in rice cultivation and related rice value chain activities in Asia. The majority of rice farmers are small holders, farming a mean land area of 0.5 ha or less [3]. Flooded rice fields also contribute to ecosystem services, such as aquatic and terrestrial biodiversity, groundwater recharge, and regulation of water flow, benefits that are often not fully recognised and appreciated by the public. Rice farming is also reasonably benign to the environment, relative to many other crops, e.g. more methane production, but little nitrate (NO_3^-) leaching, and very little herbicide use [4].

About 90% of the global rice crop is produced and consumed in Asia. The total harvested area was 145 mha, which produced 667 mt of unhusked rough rice in 2014 [5]. Major rice producers are the People's Republic of China (which has the largest rice production), followed by India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar and the Philippines in decreasing order. Other countries produce less than 11 mt of unhusked rough rice per year (Table 1). The average unhusked rough rice yield across all of Asia was 4.57 t ha^{-1} yr^{-1} in 2013, the highest yield being recorded in Australia (10.22 t ha^{-1} yr^{-1}), followed by Japan and People's Republic of China (6.72 t ha^{-1} yr^{-1}), and Taiwan (China), Vietnam and Indonesia (5.15–5.90 t ha^{-1} yr^{-1}). Rice yields in other countries were less than 5.0 t ha^{-1} yr^{-1}.

Rice is the staple food for 60% of the Asian population. Annual per capita milled rice consumption is the highest [205 kilograms (kg)] in Myanmar, followed by Bangladesh, Cambodia, Indonesia, Lao PDR, and Vietnam (149–169 kg). In these countries rice provides over 50% of the calories in their population's diet (Table 1). As the population of Asia and Oceania is projected to increase from 3.7 billion in 2000 to 5.5 billion in 2050 [6], further intensification of rice cultivation is necessary if food and nutrition security is to be maintained in the near future.

TABLE 1.1. RICE PRODUCTION AND CONSUMPTION STATISTICS OF SELECTED ASIAN COUNTRIES

Country	Unhusked rough rice production (mt) (2013)	Harvested rice area (kha) (2013)	Mean unhusked rice yield (t ha^{-1} yr^{-1}) (2013)	Mean annual per capita milled rice consumption (kg) (2002)	Share (%) of calories from rice in diet (2002)
People's Republic of China	203.61	30 311.8	6.72	83	28
India	159.20	43 940.0	3.62	83	34
Indonesia	71.28	13 835.3	5.15	149	50
Bangladesh	51.50	11 770.0	4.38	164	74
Vietnam	44.04	7902.8	5.57	169	65
Thailand	36.06	12 373.2	2.92	103	41
Myanmar	28.77	7500.0	3.84	205	68
Philippines	18.44	4746.1	3.88	105	43
Japan	10.76	1599.0	6.73	58	22
Cambodia	9.39	3100.0	3.03	149	69
Pakistan	6.80	2789.2	2.44	18	8
Republic of Korea	5.63	832.6	6.76	83	29
Sri Lanka	4.62	1188.2	3.89	91	37
Nepal	4.50	1420.6	3.17	102	38
Lao PDR	3.42	880.0	3.88	168	64
Malaysia	2.63	688.2	3.82	73	25
Taiwan, China	1.59	270.2	5.90	-	-
Australia	1.16	113.6	10.22	10	3
Total/Mean	663.49	145 290.7	4.57	-	-

Notes: t: tonne; mt: million tonnes; ha: hectare(s); kha: thousand hectares; kg: kilogram Source (Production, harvested area, yield): [7]

Over the past five decades, except during the rice price crisis of 2007–2008, a steadily increasing rice production has kept pace with human population growth, thereby providing rice at an affordable price to poor rural and urban consumers. Further increases in rice production, however, are critical in nearly all developing Asian countries mainly to feed the expanding population, but also, to a lesser extent, to meet changing dietary patterns in urban centres. This increased production will, unfortunately, be accomplished under circumstances where land and water resources are decreasing and becoming degraded [3], while emissions of greenhouse gases (GHGs) including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are increasing. Coincidentally, there is a declining availability of farm labour, coupled with increasing wages. This results in an increasing cost of, and declining profit in, rice farming. Finally, there will be imminent increases in health and safety concerns for both producers and consumers. For producers, the safety concerns are mainly due to increased and inappropriate use of chemical pesticides that could directly impact farmers and farm workers. For consumers, it is overall pollution of air by GHGs and water sources by excess nitrate and pesticide residues moving from farms to rivers and oceans, all of which have the potential to impair the health of people in the entire watershed.

1.1. BACKGROUND

Global rice markets are small and volatile. Only about 7% of global rice production is traded internationally, which results in a tight supply of, and demand for, rice throughout Asia. The four major Asian rice exporters – Thailand, India, Vietnam, and Pakistan – along with the United States of America (USA), control 87% of global rice trade [8]. Cambodia, Laos and Myanmar currently have adequate land and water resources for growing rice, not only to feed their own population, but also to potentially export surplus rice to other countries. Indonesia and the Philippines are currently significant rice importers, despite their continuing efforts to become self-sufficient in rice production.

Urbanization and out migration of rural people to cities is a growing concern in the rice production sector in Asia. Farmers are moving from villages to cities in search of good jobs and higher wages and this is occurring in all of the major rice producing Asian countries [3]. In addition, rice farming is not a very attractive career to many rural youth, who are better educated than their parents. Such trends in urbanization will increase rice consumption in urban centres and significantly reduce the labour force available for rice farming in rural areas.

Global demand for milled rice is projected to increase from 439 mt in 2010 to 555 mt in 2035. Future demand for rice in Asia will depend on the annual human population growth rate, and rice consumption, due to changing dietary patterns of the fast-growing Asian urban population [9]. For example, per capita rice intake is steadily decreasing in the People's Republic of China, Japan, South Korea, Malaysia and Thailand, while it is stable or slightly increasing in other Asian countries.

It is expected, then, that the combination of a slower growth in per capita rice consumption and increased rice output will keep the global rice prices steady, or even result in a slight decline from 2011 to 2021. For 2012, stochastic estimates of milled rice price per tonne ranged between US $405 and $549, with an average of US $471. Similarly, stochastic estimates of the global milled rice trade ranged between 32 and 43 m t, with an average of 38.3 m t. These estimates are based on assumptions of normal weather and a continuation of current policies set for the rice sector by individual Asian governments. If a country imposes rice export bans during unexpected shortfalls in local rice production in times of extreme weather events or natural disasters, which could lead to serious supply disruptions and price volatility in the global rice market (as happened in 2007–2008) [8].

1.2. TRANSITION OF RICE FARMING SYSTEMS IN ASIA:

The following sections describe the changes that took place in rice farming systems before the start of Green Revolution till now.

1.2.1. Pre-industrial traditional agriculture:

This era was a period of true Conservation Agriculture (CA), a time during which farmers developed thousands of crop varieties and many animal breeds over centuries. They accomplished this CA through natural crossing (hybridization) and the selection of crops and varieties which were adapted to local soil, biotic and abiotic, climatic (drought, flood, storms) and social conditions. Soil fertility was regenerated through long periods of rest (fallow periods of 12–18 years after 1–2 years of cropping), the periodic addition of natural materials such as household (domestic) wastes, composts and animal manures, and adopting practices such as crop rotation (especially with N fixing legumes) and mixed planting with other crop species [10]. Additional N for agriculture was obtained from mining of Chilean saltpetre (sodium nitrate) and Peruvian guano deposits, a rich source of N, phosphorus (P) and potassium (K), as well as the extraction of ammonium compounds from coal [11]. Farmers replanted their own seeds and exchanged their seeds and animal breeds with others, thereby spreading new planting materials and animal breeds far and wide, while coincidentally preserving biodiversity in farmlands. This form of preindustrial CA supported the small populations existing during those times, and all organisms (including humans) lived in what can best be termed a sort of enforced 'harmony with nature'. It was also an era when people feared that the natural sources of N and other plant nutrients would soon be exhausted as agriculture expanded and human populations grew rapidly.

1.2.2. Green Revolution Agriculture:

The development and widespread use of the semi-dwarf, short duration (100–120 days to harvest), high yielding rice varieties was supported by a liberal application of water, fertilisers and chemicals (weedicides, pesticides and insecticides). There was also a focused policy and institutional support (e.g. Intensive Agricultural Development Programmes, IADPs) which were being implemented in favorable irrigated areas. All these helped pave the way for the first Green Revolution in Asia during the period of 1970–2000. Farmers planted 2 to 3 rice crops per year and started applying increased rates of chemical fertilisers (especially urea) to achieve high yields in successive crop seasons. This happened in the North Western and Southern states of India, in Central Luzon and Mindanao of the Philippines, on the Java and Bali islands of Indonesia and on the Mekong River Delta of South Vietnam. This era produced a continuous, intensive mono-cropping of rice, which increased the annual rice productivity per unit of land, thereby helping to avert famine and reducing hunger [12, 13, 14, 15].

However, over time, the Green Revolution amplified the incidence of insect pests and diseases. This occurred mainly because the early generation of semi dwarf rice varieties was bred for high yields, though not for resistance to insect pests or diseases. Farmers therefore responded to this situation by applying larger quantities of toxic chemical pesticides against insect pests and a range of diseases. Later, the farmers began to routinely apply preventive applications of pesticides at regular intervals, instead of applications as and when their crops were attacked [16]. Even after the introduction of pest-resistant or pest-tolerant rice varieties in 1980s and 1990s, pesticide applications to rice crops did not drop, rather they increased. Despite the impressive records of food production, and avoidance of hunger and famines, there are reports of numerous adverse effects of chemical intensive monocrop production systems of cereals, including rice: i.e. resource depletion and degradation, increased GHGs [ammonia

(NH_3), N_2O, nitric oxide (NO) and CH_4] emissions, environmental pollution, and the loss of habitats and biodiversity [17, 18].

1.2.3. Post-Green Revolution Agriculture–Intensification of Ecological Concern:

The continued increase in human population growth and the consequent increased demand for food and other agricultural commodities was increasingly being pitted against mounting community concerns about intensive agriculture-related resource depletion, environmental degradation and increased pollution problems.

At the beginning of the 21st century, agricultural scientists faced their greatest challenge, one of intensifying agricultural production without harming the environment while at the same time protecting or enhancing the resource base of land and water. This is when the concept of CA-based intensification of ecologically sound farming practices began to be seriously considered as an alternative to Green Revolution agriculture. An intensification of CA-based ecological approaches is now considered to be the most appropriate option for the tropics and subtropics regions [19]. It is these two regions where climate change is likely to result in an increased frequency of severe droughts, erratic rainfall events, and an increased degradation of both agricultural and forest lands [20]. Some of the consequences, issues and challenges of the past and future phases of rice crop intensification are shown in Table 1.2 which was synthesized from the literature cited in section 1.2.

TABLE 1.2. CONSEQUENCES, ISSUES AND CHALLENGES FACING THE INTENSIFICATION OF RICE FARMING

Particulars	Pre-industrial traditional, low input agricultural systems (Prior to 1960)	High input monoculture Green Revolution Agriculture (1961–2000)	Optimum input ecologically oriented, intensive farming systems – 21st Century
Input use and efficiency			
Indigenous (farm generated) inputs	High	Low	As much as possible
External inputs (fertilisers, plant protection chemicals)	Nil	High	Optimum, as per crop demand
Agronomic N use efficiency (kg grain per kg N)	Low (5–10)	Low medium (10–15)	High (20–25)
N recovery efficiency (%)	Low (15–25)	Medium (30–40)	High (50–60)
Water productivity (grams of rice per litre of water)	Low (0.10–0.15)	Medium (0.4–0.5)	High (0.8–1.1)
Labour productivity	Low	Medium	High
Drudgery	High	Medium	Low
Yield and profit			
Yield	Low	High	High
Profitability	Low	Medium	Medium to high
Environmental impact			
Ground water depletion	Nil	High	Minimal
Pollution of water sources	Nil	High	Low
Methane emission	Low	Medium to high	Low
Nitrous oxide emission	Nil	Low	High
Rice straw burning	Nil	Medium to high	Low to nil
Sustainability			
Production sustainability	High	Low	High
Economic sustainability	Low	Low to medium	Medium to high
Environmental sustainability	High	Low	Medium to high
Total sustainability	High at low yield level	Low to medium at high yield level	High at high yield level

1.3. SMALL HOLDERS VERSUS LARGE HOLDERS RICE PRODUCTION IN ASIA: POTENTIAL, POSSIBILITIES AND ISSUES

Globally, 500+ million small holder farmers produce food which feeds 50 to 80% of the world's present population, and in Asia most of the small holders are rice farmers (https://www.ifad.org/documents/10180/ca86ab2d-74f0-42a5-b4b6-5e476d321619); World Bank 2016). For example, in India 85% of the total holdings (117.60 million) are both small and marginal, representing 44.5% of the agricultural land area (71.15 m ha). This works out to a mean holding size of 0.51 ha per farmer. In India, the customary procedure is to divide family land among sons and daughters. About 1.5 to 2.0 million new small, marginal farms are added every year [The Socio-economic and Caste Census (SECC) 2011, www.secc.gov.in/].

Small holders have little or no bargaining power in securing loans from scheduled banks (fewer than 4% of small holders have agricultural credit cards) and very few small holder farmers carry crop insurance against natural calamities, etc. In addition, small holders are especially vulnerable to climate change-aggravated weather events, like untimely rains (especially at harvest times), severe droughts and floods, hailstorms and pest infestations, any of which can wipe out crops. There are also market uncertainties and most agricultural policies (and institutional support) tend to favour farmers with large holdings and agricultural or food corporations, e.g. industrial agriculture receives 80% of the farm subsidies and 90% of any research funds.

1.4. GROWING RESOURCE SCARCITY AND RESOURCE DEGRADATION VERSUS RICE PRODUCTION

It is a fact that continuous intensive mono cropping of rice has increased rice productivity per unit of land, thus helping to increase rice productivity in Asia. However, it is also a fact that chemical intensive rice farming has produced undesirable effects, such as accelerating the depletion of land and water resources [17]. This depletion of land and water resources is due in part to an increased competition for natural resources between agriculture and other uses. Additionally (and importantly) there has been an accelerating degradation of fertile agricultural land, and thus a decline in its productivity. This situation is exacerbated by a mounting water crisis, including groundwater depletion. Other undesirable effects include a declining on-farm biodiversity and loss of natural habitats. These have the consequence of decreasing the resilience of crops to biotic and abiotic stresses. There is also an increasing pollution of soil, water and air in farming areas which impact people in the entire watershed/catchment. The pollution increases are being caused by a growing use of fertilisers and chemical pesticides, as well as by increases in GHGs emissions [18].

Globally, a quarter of the agricultural lands are classed as severely degraded and another 8% is moderately degraded [21]. An estimated 11% (34 mha) of irrigated agricultural lands are also impacted by various forms of salinity, due to inappropriate irrigation practices and poor or no drainage provisions.

There are also increases in prawn culture and seawater intrusion in coastal areas which are causing increased coastal soil salinity and alkalinity. Deforestation and destruction of vegetation in high elevation (hillside) watersheds, intensive tillage, absence of vegetation cover on arable land/soils, and excessive livestock grazing are all leading to severe soil erosion by both wind and water. Soil compaction and soil acidification and alkalisation are other important forms of increasing soil degradation [22].

Water is a scarce commodity in Asia, as 36% of the available fresh water reserves have to support 60% of the world's human population and the annual per capita availability of water is declining in all Asian countries. For example, in India, the water available per person per year has declined from 5137 m^3 (one m^3 of water equal to1000 litres) in 1951 to 1000 m^3 in 2010, and is projected to decline further to 600 m^3 by 2020. Increasing water scarcity will adversely impact rice productivity because rice crops consume more water per unit of grain production than other crops: e.g. 1500 to 3000 litres (L) are required to produce 1 kg of rice compared to 800 to 1000 L needed to produce 1 kg of wheat. With a growing intensification of agriculture, the onfarm biodiversity has declined steadily. Since 1900 approximately 75% of crop plant genetic diversity has been lost as farmers, worldwide, have abandoned traditional crop varieties and embraced high yielding varieties, the latter having a much narrower genetic base [23]. At present, just three crop plants, rice, maize and wheat contribute nearly 60% of the calories and protein consumed by humans worldwide.

Increased emissions of GHGs, especially CO_2 from excessive fossil fuel use and the burning of straw from rice and other grain crops, together with CH_4 and N_2O releases from agricultural soils have all contributed to climate change [10, 24, 25, 26]. The changing climate, in turn, produces extreme weather events (droughts, floods and storms); ones that often lead to reduced grain yields and/or complete crop failures. Finally, agriculture-related pollution by N and P fertiliser use and pesticide residues, is not restricted to farmlands, it also moves downstream causing eutrophication, and siltation of sediments in water bodies and reservoirs, thus affecting people in the entire watershed.

In general, rice farmers, consumers and even members of the general public have become increasingly aware of the enormous challenge of tackling the negative impacts of intensive farming of rice and other crops. In fact, the recent emphasis on intensive farming has endangered the ecological foundation and long-term sustainability of agriculture in general and rice farming in particular. It is especially important to increase productivity of rice and rice-based farming systems without further degradation of the natural resource base. This aim is feasible by using methods that have a minimal adverse impact on the environment.

Thus, there is a need for new rice varieties, development of climate smart agricultural practices for nutrient and water management, new production technologies and appropriate changes in rural infrastructure. Appropriate institutional support systems are needed to make intensive rice production sustainable, profitable, regenerative, and supportive of the land and water resource bases, and of the environment.

1.5. OBJECTIVE

The objective of the Rice Production Guidelines is to provide information on the best farm management practices and the role of nuclear and isotopic techniques to better understand nutrient use efficiency. The Rice Production Guidelines for Asia attempts to serve the different Asian countries by bringing together a concise information package of 'improved' technologies on rice production and post-harvest procedures which have been developed during the past five decades by the International Rice Research Institute (IRRI) Philippines in close collaboration with the different Asian national research and development institutes. These Guidelines are intended to assist farmers in learning how to adapt the new 'climate smart' rice varieties and production and post-harvest technologies that are most suited to their own circumstances in the various regions and countries of Asia.

1.6. SCOPE

The Rice Production Guidelines provide concise step wise information on best agronomic practices as well as on measuring N use efficiency using stable isotope of ^{15}N. ^{15}N technique is an ideal tracer of the fate of N in the environment. It can be easily measured in soil, plant, water or air, both in the laboratory and in the field. Thus, the ^{15}N technique is crucial to ensuring a better targeting of N applications in agricultural systems, which can't be measured precisely through non-isotopic technique.

1.7. STRUCTURE

The TECDOC consists of five chapters/sections. In chapter 1, rice farming background prior to Green Revolution till to date and objectives have been introduced. Chapter 2, focusses on the impact of climate change and rice farming constraints under different rice ecosystems. Chapter 3 covers comprehensively rice farming under low land irrigated and rainfed conditions, including varietal selection, land preparation, crop establishment, water management, soil fertility and nutrient management, weeds, insect, pest, and disease, and post-harvest management. In chapter 4, best soil farm practices for rainfed upland rice have been put together to demonstrate how farmers can increase their rice production under changing climate and limited farm inputs in rainfed condition. Chapter 5 introduces the role of nuclear technique of nitrogen-15 (^{15}N) to measure nutrient use efficiency and N dynamics in soil-plant-atmosphere system.

1.8. REFERENCES CHAPTER 1

[1] GLOBAL RICE SCIENCE PATNERSHIP (GRISP), Rice Almanac, 4th Edition, International Rice Research Institute (IRRI), Los Banos, Philippines (2013) 283 pp. irri.org/resources/publications/books/rice-almanac-4th-edition

[2] NAKAMURA, S., The origin of rice cultivation in the lower Yangtze region People's Republic of China, Archeolog. Anthropol. Sci. **2** (2010) 107–113.

[3] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. The State of Food and Agriculture. Leveraging Food Systems for Inclusive Rural Transformation (2017)

[4] BOUMAN, B., et al., Rice: Feeding the billions, In: D. Seckler (eds.) The culture of rice, Colombo, Sri Lanka, International Water Management Institute. (IWMI), (2006) 515–549.

[5] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAO-Statistical Data Base, (2017).

[6] BAKER, S., Population in Asia and the Pacific. In: The Far East and Australasia (2003) 20 pp.

[7] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAO-Statistical Data Base (2015).

[8] WAILES, E.J., CHAVEZ, E.C., Asian and global rice situation and outlook. ADB Sustainable Development Working Paper Series No. 22. Asian Development Bank (ADB), Manila, Philippines (2012).

[9] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAO-Statistical Data Base, 2012.

[10] BALASUBRAMANIAN, V., Reactive Nitrogen: Good, Bad and Ugly, Comprehensive Status Report (2010). SCON-ING, New Delhi, India, (2010) 1–52.

[11] SUTTON, M.A., et al., Ammonia in the environment: from ancient times to the present. Envir. Pollut. **156** (2008) 583–604.

[12] HERDT, R.W., CAPULE, C., Adoption, spread, and production impact of modern rice varieties in Asia. International Rice Research Institute (IRRI), Manila 1099, Philippines (1983) 1–54.

[13] DALRYMPLE, D.G., Development and spread of high-yielding rice varieties in developing countries. Metrotec, Inc., Washington, D.C. (USA) (1986) 1–117.

[14] HOSSAIN, M., FISCHER, K.S., Rice research for food security and sustainable agricultural development in Asia. Geo. Jour. **35** (1995) 286–298.

[15] HOSSAIN, M., Do lower rice prices help the poor? Rice Today **37** (2005).

[16] ROLA, A., PINGALI, P.L., Pesticides, rice productivity, and farmers' health. International Rice Research Institute (IRRI), Manila 1099, Philippines (1993).

[17] LAL, R., Restoring Soil Quality to Mitigate Soil Degradation, Sustainability 2015, 7, 5875-5895.

[18] UNITED NATIONS ENVIRONMENT PROGRAMME, Avoiding future famines: Strengthening the ecological foundation of food security through sustainable food systems, A UNEP Synthesis Report, ISBN: 978–92-807-3261-0. UNEP, Nairobi, Kenya (2012).

[19] STOOP, W.A., SABARMATEE, PUSHPALATHA, RAVINDRA, SEN. D., PRASAD, S.C., THAKUR, A.K., Opportunities for ecological intensification: Lessons and insights from the System of rice/crop intensification – their implications for agricultural research and development approaches. CAB Reviews 2017 – 12, No. 036 (2017).

[20] WALL, P., What drives the conservation agriculture revolution? International Fertilizer Industry Association (IFA), Paris, France, Fertilizer Agriculture (2011) 1–2.

[21] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, The State of the World's Land and Water Resources for Food and Agriculture (SOLAW), (2011).

[22] OLDEMAN, I.R., HAKKELING, R.T.A., SAMBROCK, W.G., World map of the status of human-induced soil degradation, Wageningen, The Netherlands: ISRIC and UNEP 2011. The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) (1991).

[23] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS Women: users, preservers and managers of agro-biodiversity (1999).

[24] BIJAY, S., TIWARI, M.K., ABROL, Y.P., Reactive nitrogen in agriculture, industry and environment in India. Indian National Science Academy, New Delhi, India (2008) pp 42.

[25] LADHA, J.K., et al., Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice–wheat system in South Asia. In: Ladha JK; Yadvinder-Singh; Erenstein O; Hardy B, eds. Integrated crop and resource management in the rice–wheat system of South Asia, International Rice Research Institute, Los Banos, Philippines. (2009) 69–108.

[26] PATHAK, H., et al., Impact of resource conserving technologies on productivity and greenhouse gas emissions in the rice-wheat system. Greenhouse Gases: Sci.& Tech. **1** (2011) 261–277.

2. CLIMATE CHANGE VERSUS RICE PRODUCTION

This chapter describes the impacts of climate change on rice production and the different types of rice ecosystems. Rice is a highly versatile crop and it is grown in a wide range of climatic conditions: from 35° South Latitude to 50° North Latitude; from the wettest areas (5100 mm annual rainfall) of the Arakan coast in Myanmar to the driest Al Hasa Oasis (annual rainfall 100 mm) in Saudi Arabia; from the hottest (mean temperature 33ºC during the rice growing season). The Upper Sind region in Pakistan to the coldest (mean temperature of 17 ºC during rice growing season) Otaru area in Japan; from sea level on the coastal plains of Asia to 2600 m elevation on the sloping mountains of Nepal; and from 25% of the potential sunlight irradiance in parts of Myanmar and Thailand and in India's Assam State, to about 95% of the potential sunlight irradiance in Egypt and Sudan [1]. Depending on the climate, rice varieties can be classified as (i) temperate climate rice, mostly grown in warm cool subtropics and cooler regions and (ii) tropical rice grown in the hot, humid and sub humid tropics.

Local weather conditions can have a large influence on production of crops that are highly sensitive to changes in climate. Most rice scientists agree that (a) rising temperatures, (b) changing rainfall patterns, (c) more frequent occurrence of extreme weather events [2], as well as rising sea levels and increasing soil salinity in coastal areas, will have appreciable and adverse effects on rice production in Asia.

2.1. RISING TEMPERATURES

According IPCC (2007), it is predicted that global warming could reduce food production by 10 to 25% in most developing countries by 2080 http://www.ipcc.ch/pdf/assessmentreport. A modest rise in temperature may be good for rice crop production, especially in cooler regions, but the continued rise in temperature can also be detrimental to rice crops, particularly in the humid tropics. A study at International Rice Research Institute IRRI farm in the Philippines indicates that the annual mean maximum temperatures have increased by 0.35°C, and the mean minimum temperatures by 1.13°C, for the period 1979–2003. There is a close linkage between rice grain yield and mean minimum (night) temperature during the dry cropping season (January to April). Thus, grain yields declined by 10% for each 1°C increase in growing season minimum temperature in the dry season, whereas the effect of maximum temperature on crop yield was not significant [3].

With an increasing temperature and its associated water stress, a crop plant's resistance to pests is often lowered. Thus, crop damage from insect and fungal pests, especially, can likely be expected to increase dramatically in the near future [4, 5].

2.2. CHANGING RAINFALL PATTERNS

Climate change affect rainfall distribution; therefore, rainfed lowland and upland rice crops will likely suffer the most, due to changes in, and unpredictability of, rainfall patterns. Both unexpected droughts and floods, which occur during the crop's growing season, will also limit crop growth, increase pest and disease infestation, and reduce grain yields and grain quality, thereby increasing food insecurity [5]. About 20 mha of the world's rice growing area are at risk of occasional flooding, particularly in major rice producing countries such as India and Bangladesh. Unexpected rainfall events at the time of harvest can cause tremendous difficulties to rice farmers. Lodging of mature rice crops will occur, thus increasing the difficulty of harvesting the grain. Grain threshing and sun drying will become more difficult and there are increased losses in quantity and quality of grains which are harvested. In Asia, large areas of low lying deltas and coastal areas such as the Mekong River delta in Vietnam and the Ganges basin in Bangladesh and India are under rice crop production. With rising sea levels, saltwater will penetrate more frequently into inland areas. This will contribute to coastal soil salinity and radically reduce rice yields, as most rice varieties are only moderately tolerant to salinity. A one meter rise in sea level could wipe out the prime rice production areas in many Asian countries [6].

2.3. EXTREME WEATHER EVENTS

Extreme weather events caused by climate change bring natural disasters, such as floods, droughts and tropical cyclones, can damage or destroy farming and general infrastructure and adversely impact trade by disrupting transportation, supply chains and other logistics [7, 8]. Climate change is expected to have decisive impacts on many global environmental and resource issues such as desertification, depletion of water resources, shrinking glaciers, ocean acidification, loss of corals and nurseries for fish, and eventually a reduced level of human health.

2.4. INCREASING CO_2 CONCENTRATION

Warmer weather can increase rice production in cooler regions and to a certain extent in the tropics, but other factors such as available water, soil properties, nutrients, and crop growing days within certain temperature ranges will ultimately limit crop growth. Increased water scarcity due to climate change will reduce production of rice and other food crops; this will have serious implications for food security, and human nutrition and health [5].

An elevated concentration of atmospheric CO_2 [546 to 586 parts per million (ppm)] is known to lower the uptake of zinc and iron and reduce protein by 5 to 10%, increase starch and sugar contents in major food crops such as rice, wheat, peas and soybean, but not in maize and sorghum [9]. Lower levels of dietary iron and zinc can impair human health by increased occurrence of anemia, a weakened immune system, a lower intelligence quotient (IQ), and fatigue due to lower body energy.

2.5. CLIMATE MITIGATION AND ADAPTATION MEASURES – CLIMATE SMART RICE PRODUCTION TECHNOLOGIES

Small holder farmers worldwide have been selecting crop varieties and adapting farm practices for a slowly changing climate for thousands of years. However, changes in local weather and climatic conditions due to human activities are beginning to disrupt crop production in an unprecedented manner. Development of climate smart agricultural practices to combat the negative impact of climate change is needed to ensure food security for growing human population. A useful approach may be one which combines farmers' local knowledge and traditional coping practices with valid scientific discoveries and technologies. Some climate mitigation options are discussed below.

2.5.1. Rehabilitation of watersheds

In deforested upper watershed areas, improving vegetation cover, reducing soil erosion and reviving local headwater streams is needed to stabilise the water flow to downstream areas. These objectives can be accomplished through afforestation, sustainable forest management and reducing or eliminating deforestation.

2.5.2. Management of farming areas – 'Climate smart agriculture'

In farming areas, the most cost-effective mitigation options are to improve crop and grazing land management practices and restore organic matter in the soil. In addition, reviving of small streams, rivers and lakes and protecting wetlands, including mangrove ecosystems in subtropical coastal regions are also needed as part of climate smart agricultural practices. Farmers may reduce greenhouse gas emissions from agricultural activities through adaptation, mitigation and food security using 'climate smart agriculture' [6].

If farmers increase the soil organic matter in their fields, then carbon (C) storage will also be increased – a mitigation function. Additionally, more organic matter also means better soil quality, higher nutrient and water holding capacity, and higher crop yields, all being combined with an increase in nutrient use efficiency. Other things that farmers can do on their own include increasing crop diversity, or changing the planting dates to better fit changing rainfall patterns or shortening crop growing seasons.

Other important actions, taken by national or local governments, include building irrigation drainage facilities for farmers to cope with changing rainfall patterns. There is an adequate supply of good quality seeds and other farm inputs at the right price. Governments can assist in the building of large processing facilities and improve the access to key markets. Government support for rural education, health and renewable energy infrastructure is imperative. Finally, favourable policy and institutional support are critical for:

- Identifying climate related risks and stresses along the entire value chain;
- Breeding rice varieties that are more tolerant of climate related abiotic stress (drought, flood, cold and high temperature) and also have increased resistance to biotic stressors (insect pests and diseases);
- Deployment of scientific findings and technologies to make farming practices much more efficient at using natural resources of soil, water, and energy, while optimizing necessary external inputs, including fertilisers and pesticides;
- Equipping and empowering small holder farmers to adopt ecologically sound conservation agriculture practices. These will include improving soil health and fertility, a better management of water and energy resources, enhancing biodiversity both onfarm and off-

farm, implementing appropriate farm mechanization, and using agroforestry systems whenever feasible;

- Enhancing the adoption of small holder crop animal production systems as a means to improve cash flow, family nutrition and health, and resilience against abrupt changes in weather and or markets;
- Moving rice production to, or intensifying rice production in, new untapped areas with abundant water resources (e.g. Eastern India, Myanmar and Cambodia).

2.6. MODERATING FOOD DEMAND AND CHANGING FOOD CONSUMPTION PATTERNS

It is reported that annual human population growth rate in Asia is projected to decrease from 1.2% (the rate during 2000–2005) to 0.1% by 2050 [7].

The two most important human nutrition challenges are under nourishment and overeating and obesity related chronic diseases. Worldwide, 795 million people who go to bed hungry suffer from inadequate intake of calories and protein [10]. On the other extreme where excess food is produced, people aren’t fed better either; an estimated 1.5 to 2.0 billion people suffer from hidden hunger or micronutrient deficiencies and chronic diseases like obesity, cardio vascular problems, and diabetes due to poor quality diets [11]. More food need to be produced in places where people starve to reduce hunger and malnutrition, while provision of nutrition education is critical for the other group to reduce excessive eating and to change their dietary patterns by consuming more nutritious foods which will lead to better health.

2.7. RICE ECOSYSTEMS

Most classifications of rice environments are based on hydrological characteristics which are appreciably influenced by the location of rice growing lands on the topography. Typical rice ecosystems are shown on the following ‘topo sequence’ (Fig. 2.1). They start with upland rice at the top (plateau and sloping lands) and move down to flood prone rice croplands near the riverbanks. Rainfed, lowland rice occurs at two locations – on hydromorphic, gently sloping edge lands, and also in the valley bottom. Irrigated rice is commonly found in floodplains along rivers. There are two types of estimated rice areas: (a) a physical rice area that changes only when new land is brought under rice cultivation and (b) a harvested rice area as determined by the number of rice crops grown in the same piece of land per year (the latter changes from year to year due to changes in availability of rain or irrigation water, factors which determine the number of rice crops grown the same piece of land in different years). The percentage of physical rice area classed in different ecosystems is: upland rice 9.6%, irrigated rice 54.7%, rainfed lowland rice 32.7%, and flood prone + floating rice 3.0% [12, 1, 13].

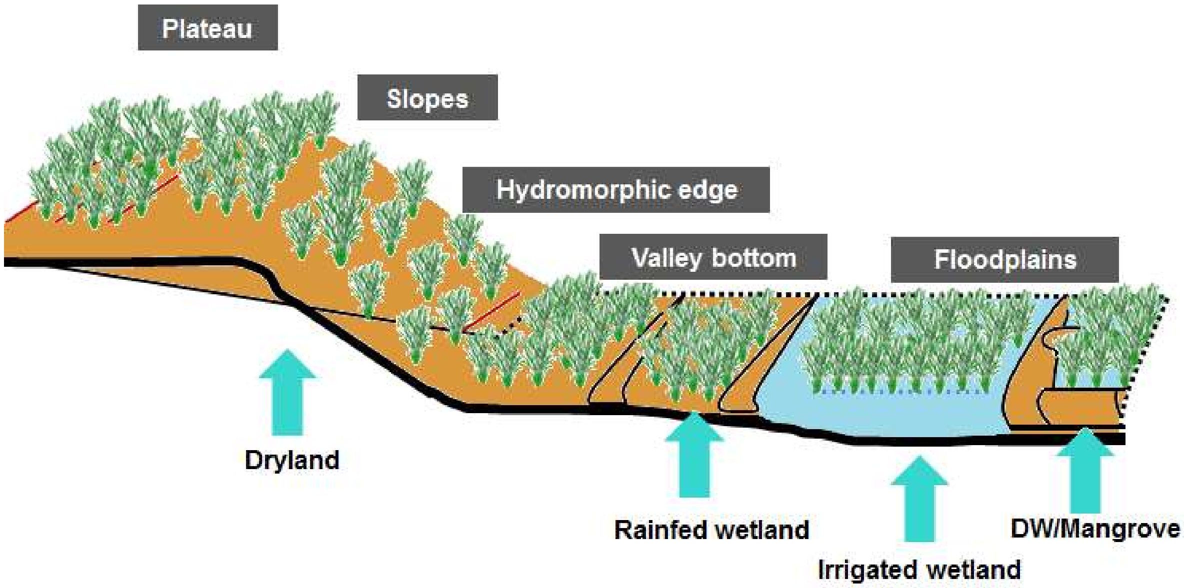


FIG. 2.1. Schematic diagram showing major rice ecosystems on a topo sequence adopted from Balasubramanian [14].

2.7.1. The irrigated rice ecosystem

An Irrigated Rice ecosystem is characterised by bunded fields with water control. Soil is mostly puddled and levelled, rice seedlings can be transplanted or rice can be wet seeded. A shallow water level is maintained during the crop growth period. Of the global physical irrigated rice area of 82 mha, 74 mha are found in Asia [1]. The irrigated rice ecosystem provides three fourths of the world's rice production, and it is concentrated in the humid and sub humid tropics. It is also characterised by high cropping intensity and currently has a high use of chemicals.

Depending on the rainfall variability, the irrigated rice ecosystem can be divided into two classes, irrigated wet season (WS) area and irrigated dry season (DS) area. In the irrigated WS area, rainfall is supplemented by irrigation, as and when needed. Solar irradiance is reduced due to frequent cloud cover, and yields are relatively low (4–5 t ha^{-1}). In an irrigated DS area, the rice crop is fully dependent on irrigation as rainfall is low, solar irradiance is high, and yields are high around 8 t ha^{-1} or more.

Based on grain yield, the irrigated rice ecosystem is divided into 3 zones: There is a higher yield zone with mean yields > 5 t ha^{-1} (Australia, People's Republic of China, Indonesia, Japan and Vietnam); a medium yield area with 4–5 t ha^{-1} (India, Malaysia, Philippines, and Thailand); and a low yield area with < 4 t ha^{-1} (Cambodia, Laos, Myanmar, Nepal and Pakistan).

In the irrigated rice ecosystem production constraints include: poor use and management of inputs, unstable yield due to pest pressure, poor land preparation, i.e. poor levelling and/or irrigation management. There is also inadequate drainage (leading to salinity and alkalinity), and difficulty in sustaining high yields in what is currently managed as a chemical intensive cropping system.

2.7.2. Rainfed lowland rice ecosystems

A rainfed lowland rice ecosystem is one which is characterised by level to slightly sloping, bunded fields, ones which have a non-continuous flooding. The rice crop is established by direct seeding or transplanting. The rainfed lowland rice ecosystem constitutes about 34.1% (45 mha) of Asia's physical rice growing area, which totals 132 mha. The main problem which occurs in the rainfed lowland rice ecosystem is the lack of water control, with both droughts and floods being common for many of the rainfed lowlands.

There are four sub ecosystems in the rainfed lowland rice ecosystem: favourable rainfed, drought prone, submergence prone, and drought and submergence prone. Generally, one rice crop is rotated with a suitable other (non-rice) crop, though this depends on the length of the rainy season and availability of water for supplementary irrigation. Production constraints include: unpredictable rainfall, drought, flood, improper soil, nutrient and water management practices, pests, weeds, use of traditional low yielding varieties, and lack of suitable production technologies.

2.7.3. Flood-prone, deep water rice ecosystems

The flood-prone rice ecosystem is characterised by slightly sloping land and a medium to deep (50 to 100 cm) flooding for more than 10 days. This results in alternating aerobic and anaerobic conditions. Flood prone rice ecosystems constitute 3% of the 132 mha of rice growing area in South and South East Asia. Examples are: Flood plains and deltas of India and Bangladesh; Irrawady delta of Myanmar; Mekong delta of Vietnam and Cambodia; and Chao Phraya of Thailand. The Niger of West Africa and lowlands of Madagascar are also characterised by use of flood prone deep water rice ecosystems.

In flood-prone rice areas, rice is grown during rainy season and other crops are grown during the dry winter season. Rice is direct seeded or transplanted. In some parts of eastern India and Bangladesh, 'boro' (a Bengali word meaning irrigated crop cultivation during November to May period) rice is grown during late winter season with the help of irrigation.

There are four types of flood-prone rice ecosystems: medium submergence (less than 50 cm water depth), deep water (50 to 100 cm water depth), very deep water or floating rice lands (more than 100 cm water depth), and tidal wetlands including mangrove swamps.

Constraints to rice production in flood-prone rice ecosystem include: very low use of fertilisers and other inputs; lack of suitable rice varieties, a low tolerance of the rice plant to submergence, salinity and acidity; and a low and extremely variable yield due to soil problems and the occurrence of unpredictable periods of drought or flood.

2.7.4. Upland rice ecosystems

Upland rice (UR) is grown in mostly unbonded fields which are level to steeply sloping. The UR fields are rarely flooded and soil remains mostly aerobic. The UR ecosystem constitutes about 9.6% of the global physical rice area (150 mha), with 9 mha of upland rice in Asia, 3 mha in Latin America, and < 2 mha in Africa.

Rice in the UR ecosystem is grown in low lying valleys (high altitude lowlands or montane paddies as commonly occur in Laos), on undulating and steeply sloping hills in Southeast Asia; on both hilly and flat land in India and West Africa, and on level to gently rolling land in Brazil. Dry, direct seeding is the common practice for crop establishment. In small holder farms, the UR rice is often mixed with (intercropped with) other crops and it can also be rotated with other crops [14].

Both biological and physical constraints limit UR yields. Biological constraints include weeds, blast disease, brown spot, stem borer, rice bug, nematode and rats. Physical constraints include: erratic rainfall, low soil fertility, soil acidity, nutrient toxicity, soil erosion and unfavourably low temperatures in high altitude areas.

2.8. RICE PRODUCTION CONSTRAINTS IN IRRIGATED LOWLAND RICE ECOSYSTEMS

These include bio-physical, management and socio-economic constraints that impact rice crop production, and vary with each rice ecosystems.

2.8.1. Rice production constraints in irrigated lowland rice ecosystems

Biophysical constraints: Yield instability is caused by weeds (particularly in direct seeded rice), insect pests, diseases, and N and P deficiency for all soil types. There are increasing secondary nutrient [potassium (K), sulphur (S) and silicon (Si)] and micronutrient zinc (Zn) deficiencies in the intensive rice producing areas and iron (Fe) and manganese (Mn) toxicity also occurs on poorly drained sites, and in peat soils with high organic matter content [15, 16, 17].

The K or Si deficiencies can also increase the susceptibility of the rice crop to diseases. Blast disease, rice gall midge (RGM), rice tungro virus (RTV), and glume discoloration are the major diseases that attack rice plants in lowland irrigated rice ecosystems. Stem borers, rats, and birds are other pests that attack rice in all ecosystems.

Management constraints: Poor land preparation, including levelling, and poor irrigation management; inadequate drainage which can lead to the development of salinity and alkalinity (inland basins and coastal wetlands); poor nutrient management; a deteriorating irrigation infrastructure, especially in the large public irrigation schemes; and over exploitation of groundwater which results in groundwater depletion.

Smaller farmer managed irrigation schemes may be a viable alternative for sustainable irrigated rice production in the irrigated lowland rice ecosystem.

2.8.2. Rice production constraints in rainfed lowland rice ecosystems

Biophysical constraints: Abiotic constraints include variable rainfall, poor water control, and unpredictable droughts and floods, occurrences that are being aggravated by Climate Change. Soils are generally poor and can be deficient in N, P, K and Zn. There is also toxicity from excessive Fe, Al, and Mn, which often occurs in wetland soils of the humid tropical zones [17, 18], as well as in poorly drained soils of coastal wetlands. Salinity and alkalinity occur in the drier and desert inland areas [19]. Weeds are the principal biotic constraint, followed by insect pests (stem borers, rice gall midge, and rice bugs) and diseases (blast and brown-spot). Rice tungro virus is a major scourge in the rainfed lowland rice ecosystem and can sometimes lead to total crop failure. In addition, rats and birds are serious problems in all ecosystems.

Management constraints: Poor or no rainwater harvesting and very little development of farm ponds for use in supplementary irrigation; poor land levelling and in-field water management; use of traditional, low yielding rice varieties and lack of suitable production technologies.

2.8.3. Rice production constraints in deep water rice ecosystems

Biophysical constraints: Unpredictable droughts and floods; submergence for 2 weeks or more due to continuous heavy rain and inadequate drainage; salinity, acidic sulphate-rich soils (soil acidity), and Fe and Mn toxicity in coastal wetlands [17] and also in peat soils**.** Cold injury at the seedling stage is also a constraint in high altitude areas [15].

Management constraints: Use of low yielding (though adapted) traditional rice varieties, the application of few or no inputs, and lack of suitable rice cultivars which are tolerant of long submergence and the other stresses, e.g. salinity, acidity, Fe and Mn toxicity, and too low (cold) temperatures at the seedling stage.

2.8.4. Rice production constraints in rainfed upland rice ecosystems

Biophysical constraints: Both abiotic and biotic constraints limit rice production in the uplands rice ecosystems. Serious abiotic constraints include variable and poorly distributed rainfall, with unpredictable dry spells. Relatively favourable temperatures occur during the crop growing season in most parts of these ecosystems, except in the tropical highlands of South, South East and East Asia where low temperature is a problem for early stage rice seedling development and growth. Low temperatures at the reproductive stage will also adversely impact grain filling. Drought can be another serious problem for rainfed upland ecosystem rice, as noted above. There is also a problem with shallow soil depth and the occurrence of surface crusting in some soils.

The soils are often erosion prone and multiple nutrient deficiencies limit crop growth and development and thus reduce grain yields. Degradation of soil structure and surface sealing (soil compaction) can constrain crop emergence and growth in semi-arid areas [20]. Dryland rice also requires extensive weeding to get a decent yield and, in such frequently cultivated systems, topsoil erosion can be a serious problem, especially on slopes.

Among biotic factors, weeds are the most serious factor for rice on dryland sites, though blast and brown spot diseases follow in importance. Estimated yield losses due to weeds range from 30% to 100% and losses of soil N due to weed infestation can reduce rice yields drastically [21]. Stem borers and rice bugs are the major insect pests. Nematodes are a serious problem in continuously mono cropped upland rice fields [22, 23] and can reduce yields by up to 30%. Termites are also a problem in some areas and rodents and birds damage rice crops in all ecosystems.

Management constraints: Poor land configuration (ridges and furrows), absence of contoured live hedges or barriers to soil movement; improper tillage and absence of soil cover (mulch) which then lead to soil erosion and loss of soil moisture; removal of trees from farms that can aggravate high temperature effect on crops and reduced addition of tree leaves that could enrich soil organic matter; slash and burn cultivation with shortened fallow periods (only 2–3 years of fallow for every 1–2 years of cropping); use of poor quality seeds and improper planting or seeding methods; poor weed control; the ‘mining’ of soil nutrients due to subsistence farming and inadequate addition of organic manures and/or fertilisers; and a continuous mono cropping with rice.

2.8.5. Human resource constraints

Human resource constraints are common to all rice ecosystems. They include the inadequate education or training of small holder rice farmers. An increasingly ineffective agricultural extension service and poor support systems are also major constraints to intensifying rice production in all ecosystems, but particularly so in both rainfed lowland and upland areas. Training and deploying adequate technical staff help to (a) strengthen the extension system, (b) improve surface irrigation management and water allocation services, (c) develop appropriate mechanization and farm machine rental services, (d) link small holder farmers to the agricultural value chain for efficient procurement of inputs and marketing of their produce, and (e) manage government supported farm credit systems and crop insurance schemes against unforeseen crop losses due extreme weather events and natural disasters. All of (a-e) above are critical factors for intensifying sustainable rice production in all rice ecosystems [14].

2.8.6. Socio-economic and policy related constraints

In addition to biophysical and human resource constraints discussed above, rice production in Asia is also affected by socio-economic and policy constraints, including:

- Unfavorable input and output pricing policies at the national level. Low output prices vis-a-vis high and rising input cost. This reduces profit and inhibits the competitiveness of small holder farmers in local, regional, and global markets;
- Limited access to credit, to important inputs (seed, fertilisers, pesticides, farm machines and implements, etc.), to markets, and to market information;
- Poor rural infrastructure (roads, transport, education and health facilities) and a lack of processing, storage and transportation facilities, specifically in Cambodia, Laos, Myanmar, and Nepal.

The establishment of efficient marketing systems requires a high level of trust between local traders and farmers, and also between local and urban traders. Prerequisites for development of efficient marketing systems are (a) the improvement of rural infrastructure and transportation systems and (b) the availability of fertiliser responsive ‘improved’ rice varieties and also the availability of efficient technologies that enhance the profitability of long-term transactions between farmers and traders. Experience shows that socio-economic institutions are not rigid, but are subject to change as new profitable opportunities arise [24, 25, 26].

2.9. CONSERVATION AGRICULTURE FOR RICE-BASED FARMING SYSTEMS

Agriculture is complex and Conservation Agriculture (CA) is even a more complex system. Therefore, moving from conventional, tillage-based, chemical intensive cereal (rice) production systems to a CA-based, ecologically sound intensive agriculture system will be complicated. Farmers will have to modify many practices including tillage/land preparation, crop residue management, type of planting and design of planting machines, methods of onfarm water/rainfall management, weed control and insect pest and disease management procedures, use of crop rotation and intercropping methods, and timing and methods of fertiliser application [27, 8].

Other limitations to adoption of CA will include a limited availability of locally adapted resource conserving technologies (RCTs), i.e. the training and education of farmers and the onfarm adaptation of RCTs to their use in both large and scattered small fields. Also of importance will be the development of focused institutional and policy support, including incentives and crop insurance, for the extension and adoption of CA practices in resource-poor, risk-prone, marginal areas [14].

Flooded rice ecosystems are often less amenable to CA practices. Here, wet ploughing, puddling and levelling are needed to prepare a smooth bed for transplanting tender, young rice seedlings or for wet direct seeding of sprouted rice seeds. Repeated ploughing and puddling creates a hardpan just below the plough layer. That hardpan helps maintain water in rice fields for longer times, as it prevents percolation or movement of water below the plough layer. Most of the flooded rice systems are concentrated in basins of flood plains and deltas near rivers. However, they also include high altitude lowlands and mountain paddies (as occur in Laos), and valley bottoms (as in West Africa), areas where there is an accumulation of water and nutrients from upper slopes and a low risk of soil erosion. This is the main reason why monsoon rice cultivation in lowlands has been sustained, albeit at a relatively low yield level of about 2–3 t ha^{-1}, over thousands of years in Asia.

Moving from wet puddled rice ecosystems to unpuddled, aerobic rice systems will open the way for incorporating more desirable CA practices, e.g. there will be a reduced tillage requirement and an increase in the use of mulching (for soil cover) to reduce evaporation from the soil surface and to control weed infestations. Use of the aerobic rice system will also allow for crop diversification through rotating and or intercropping rice with non-rice crops or even planting trees (on bunds) (Fig. 2.2). Positive impacts of aerobic rice systems also include: reduced tillage, and reduced water and energy (diesel) use (for tillage, pump irrigation and weeding). There will also be an increase in biodiversity with crop rotation and intercropping, as well as the planting of trees on rice field bunds. Implementing CA means the elimination of burning rice straw (thereby reducing CO_2 emission); and CA will also result in reduced methane CH_4 emissions.

However, aerobic rice ecosystems do pose several problems. These include unstable yields, increased weed infestation, development of weeds with increased herbicide resistance, increases in termite attacks and nematode problems, increased micronutrient deficiency, and increased N_2O emission from the aerobic soil. Research is ongoing to minimise negative impacts and maximise positive outcomes of unpuddled aerobic rice ecosystems.

(a) (b) (c) (d)

FIG. 2.2. Mulching and diversification of aerobic rice crops: (a) Unpuddled aerobic rice with mulch, and (b) rice-maize, (c) rice-cocoa and (d) rice-poplar trees intercropping systems (Photos by V. Balasubramanian).

2.10. ECOLOGICAL INTENSIFICATION THROUGH INTEGRATED RICE-BASED FARMING SYSTEMS: OPPORTUNITIES AND CHALLENGES

Globally, the expected demand – caused by human population growth – for food and other agricultural products is projected to double by 2050 [28]. It is estimated that only 7% to 12% of the projected food production required to meet this 'demand' is likely to come from the expansion of arable land areas [29]. If the demand for food and other agricultural products is to be met, then most of any increase will have to come from intensification of existing production systems. Current estimates are that 13–15% will be derived from an increased cropping intensity and 75–76% from increased yields per unit land area [29]. These increases can be achieved sustainably only through ecologically sound and climate smart agricultural methods of farming.

An enhanced productivity of rice and other crops which will be grown in rice-based farming systems is possible. But, it will come about only by combining intensive rice production technologies with CA, e.g. the use of rice farming practices which will 'conserve' the land and water base resources, as well as reduce other environmental impacts.

Some of the new technologies which will need to be implemented include laser aided land levelling, reduced or zero tillage and direct/drill seeding, precise water management, crop diversification, and site specific and crop need-based plant nutrient management. If implemented across Asia such eco-efficient practices are expected to raise land and water productivity, improve resource use efficiency, reduce risks and vulnerability of cropping systems to Climate Change, diversify farm income, and improve family nutrition and livelihood.

A comprehensive understanding of scientific, technical, environmental, economical and societal issues including education of farmers and stabilisation of the human population is a prerequisite to effectively implementing eco-efficient farming practices [30]. There is, however, no assurance that all the necessary prerequisites will be met, yet the food security of billions of human beings depends on success in implementing a truly sustainable agricultural ecosystem(s) for growing rice across Asia.

2.11. REFERENCES CHAPTER 2

[1] GLOBAL RICE SCIENCE PATNERSHIP (GRISP), Rice Almanac, 4th Edition, International Rice Research Institute (IRRI), Los Banos, Philippines (2013) 283 pp. irri.org/resources/publications/books/rice-almanac-4th-edition

[2] AVAGYAN, A., et. al., Learning tool on Nationally Appropriate Mitigation Actions (NAMAs) in the agriculture, forestry and other land use sector. FAO, Rome (2015).

[3] PENG, S., et al., Rice yields decline with higher night temperature from global warming, Proc. Nat. Acad. Sci. USA, **101** (2004), 9971–9975.

[4] GARNALL, J., BELTS, R., BURKE, E., Implications of climate change for agricultural productivity in the early twenty-first century, Biol. Sci. **365** (2010) 2973–2989.

[5] Physicians for Social Responsibility (PSR), Climate change and famine (2012).

[6] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, The Future of Food and Agriculture: Trends and Changes, www.fao.org/3/a-i6583e.pdf (2017).

[7] WAILES, E.J., CHAVEZ, E.C., Asian and global rice situation and outlook. ADB Sustainable Development Working Paper Series No. 22. Asian Development Bank (ADB), Manila, Philippines (2012).

[8] WALL, P., What drives the conservation agriculture revolution? International Fertilizer Industry Association (IFA), Paris, France, Fertilizer Agriculture (2011) 1–2.

[9] MYERS, S.S., et al., Increasing CO_2 threatens human nutrition, Nature, **510** (2014) 139–142.

[10] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, The State of Food Insecurity in the World 2015 – Key Messages (2015).

[11] NG, M., et al., Global, regional and national prevalence of overweight and obesity in children and adults during 1980–2013: a systematic analysis for the global burden of disease study 2013, (2014) 1–16.

[12] HAEFELE, S.M., BOUMAN, B.A.M., Drought-prone rain-fed lowland rice in Asia: Limitations and management options. In: Drought frontiers in rice, (2009) 211–232.

[13] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAO-Statistical Data Base (2015).

[14] BALASUBRAMANIAN, V., et al., Integrated crop management for enhancing yield, factor productivity, and profitability in Asian rice farms. Int. Rice Comm. (FAO) Newsletter **54** (2005) 63–72.

[15] BALASUBRAMANIAN, V., et al., Rice soil constraints and fertility management in the highlands of Madagascar, In 'Fragile lives in fragile ecosystems: Proceedings of the International Rice Research Conference, 13–17 February 1995, Los Baños, Philippines', Los Baños, Philippines: IRRI (1995) 313–324.

[16] SAHRAWAT, K.L., et. al., The role of tolerant genotypes and plant nutrients in the management of iron toxicity in wetland rice, J. Agric. Sci. Camb. **126** (1996)143–149.

[17] SAHRAWAT, K.L., Iron toxicity in wetland rice and the role of other nutrients, J. Plant Nutr., **27** (2004) 1471–1504.

[18] BUDDENHAGEN, I.W., Strategies and approaches to wetland rice improvement. In 'The wetlands and rice in sub-Saharan Africa: Proceedings of an international conference on wetland utilization for rice production in sub-Saharan Africa held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 4–8 November 1985' (A.S.R. Juo and J.A. Lowe, Eds.), Ibadan, Nigeria, IITA (1986) 97–106.

[19] VAN ASTEN, P.J.A., et al., Actual and potential salt-related soil degradation in an irrigated rice scheme in the Sahel zone of Mauritania, Agric. Water Manag. **60** (2003) 13–32.

[20] ANDRIESSE, W., FRESCO, L.O., A characterization of rice-growing environments in West Africa, Agric. Ecosys. Environ. **33** (1991) 377–395.

[21] BECKER, M., JOHNSON, D.E., Cropping intensity effects on dryland rice yield and sustainability in West Africa. Nutr. Cycl. Agroecos. **59** (2001) 107–117.

[22] PLOWRIGHT, R.A., HUNT, D.J., Plant parasitic nematodes of dryland, hydromorphic and inland swamp rice ecosystems in Côte d'Ivoire, Afro-Asian J. Nemat. **4** (1994) 61–67.

[23] COYNE, D.L., SAHRAWAT, K.L., PLOWRIGHT, R.A., The influence of mineral fertilizer application and plant nutrition on plant-parasitic nematodes in dryland and wetland rice in Côte d'Ivoire and its implications in long-term agricultural research trials, J. Exp. Agric. **40** (2004) 245–256.

[24] HAYAMI, Y., KIKUCHI, M., A rice village saga, Barnes & Noble, Lanham, New York (2000) 1–248.

[25] HAYAMI, Y., KIKUCHI, M., Asian village economy at the crossroads, Johns Hopkins University Press, Baltimore (1982).

[26] HAYAMI, Y., RUTTAN, V.W., Agricultural development: An international perspective, John Hopkins University Press, Baltimore (1985).

[27] JAT, M.L., SAHARAWAT, Y.S., GUPTA, R., Conservation agriculture in cereal systems of South Asia, Nutrient management perspectives, Karnataka, J. Agric. Sci. **24** (2011) 100–105.

[28] KEATING, B.A., et al., Eco-efficient agriculture, concepts, challenges and opportunities, Crop Sci. **50** (2010)109–119.

[29] FISCHER, G., et al., Climate change impacts on irrigation water requirements, Effects of mitigation, 1990–2080, Technol. Forecast. Soci. Chang. **74** (2007) 1083–1107.

[30] BALASUBRAMANIAN, V., ADHYA, T.K., LADHA, J.K., Enhancing Eco-Efficiency in the Intensive Cereal-based Systems of the Indo-Gangetic Plains. In: Issues in Tropical Agriculture, Eco-Efficiency, From Vision to Reality, CIAT, Cali, Columbia (2012).

3. PRODUCTION GUIDELINES FOR IRRIGATED AND RAINFED LOWLAND RICE-BASED FARMING SYSTEMS IN ASIA

This chapter attempts to bring a concise information package on 'improved' technologies on rice production under irrigated and rainfed lowland conditions and post-harvest procedures in different Asian countries.

FIG. 3.1 Continuous cultivation of 2–3 rice crops per year in lowlands/wetlands. The rice crops are in different stages of growth a situation which favours pest and disease build up and results in long-term soil degradation, Java, Indonesia [1].

3.1. INTRODUCTION TO IRRIGATED AND RAINFED LOWLAND RICE ECOSYSTEMS IN ASIA

'Rice producing Asia' encompasses all countries in Asia except Mongolia and countries in Central Asia. This major rice producing region represents 88% of the global physical rice area and 90% of the world's rice production. Of the 90% of the global rice produced in Asia, 87% is consumed within the region, with only 3% being exported to the rest of the world. The rice is produced either as a mono culture crop, or in rotation with other crops, in four different rice ecosystems – irrigated lowlands, rainfed lowlands, flood prone or deep water lowlands and the uplands. There are two types of designated rice areas: (a) the physical area that changes only when new land is brought under rice cultivation and (b) the harvested area as determined by the number of rice crops grown on the same piece of land per year. This latter area changes from year to year due to differences in the availability of rain or irrigation water, which are the major, factors determining the number of rice crops grown on the same piece of land in different years. Irrigated and rainfed lowland rice ecosystems are the key rice producing areas and they occupy ca. 87.4% of the global physical rice area and contribute 94% of the world's rice production. The other two rice ecosystems, viz., uplands and flood prone or deep water lowlands, occupy about 12.6% of the physical rice area but contribute only 6% of the global rice supply (Table 3.1) [2, 3, 4].

TABLE 3.1. ESTIMATED PHYSICAL AND HARVESTED RICE CROP AREAS IN DIFFERENT RICE ECOSYSTEMS. AREAS ARE SHOWN FOR THE WORLD AND FOR ASIA, AS IS THEIR CONTRIBUTION TO THE GLOBAL AND ASIAN RICE SUPPLY

	World			Asia		
Rice ecosystems	Area (mha)	% of physical rice area	% of global rice supply	Area (mha)	% of physical rice area	% of Asian rice supply
Irrigated lowlands	82.0 (93.0)	54.7	75.0	74.0 (84.0)	56.1	76.0
Rainfed lowlands	49.0 (52.0)	32.7	19.0	45.0 (48.0)	34.1	18.0
Flood prone deep water lowlands	4.5 (4.5)	3.0	2.0	4.0 (4.0)	3.0	2.0
Rainfed uplands	14.5 (14.5)	9.6	4.0	9.0 (9.0)	6.8	4.0
Total	150 (164)	100	100	132 (145)	100	100

Note: Rice area values shown in parentheses represent the rice area harvested in 2013. Source: [2, 3, 4]

3.1.1. The Irrigated rice ecosystem

Irrigated rice ecosystems in Asia are concentrated mostly in the humid and sub-humid tropics. Irrigated rice based cropping systems are practiced on alluvial floodplains (e.g. Indo Gangetic Plains in India), terraced fields on mountain slopes (e.g. the terraced rice fields of Bali, Indonesia or the mountain paddy of northern Laos), inland valleys (as commonly found in southeast Asia, e.g. Bac Son Valley bottom rice fields), and river deltas (e.g. Red River Delta and Mekong Delta in Vietnam).

The global physical irrigated rice area is 82 mha. Approximately 74 mha (88%) are located in Asia. The countries with large irrigated rice areas are People's Republic of China (31 mha), India (19 mha), Indonesia (7 mha), and Vietnam (3 mha). In some parts of eastern India and Bangladesh, 'boro' (a Bengali word which means an 'irrigated crop cultivated during the

November to May period') rice is grown during the late winter season with the help of irrigation. Overall, irrigation-based rice cropping systems provide ca 75% of the global rice supply.

(a) (b) (c) (d)

FIG. 3.1. Examples of four types of irrigated rice ecosystems in Asia: (a) Indo Gangetic flood plains, northern India, (b) Terraced rice fields, Bali, Indonesia, (c) Bac Son Valley rice fields, Vietnam and (d) Mekong Delta rice fields, South Vietnam.

Of all the irrigated rice ecosystems, rice terraces formed on mountain slopes in South East Asia, People's Republic of China, Eastern India, Nepal, and Sri Lanka are the most picturesque and visually fascinating. This unique ecosystem provides humans with several services: (a) provision of food, (b) water availability through rainwater harvesting and conservation, (c) erosion control and prevention of landslides, (d) climate control (cooling effect), (e) resilience against sudden changes, (f) pest control, (g) habitat for wildlife, and (h) cultural services (ecotourism).

Depending on the variability of rainfall, the irrigated rice ecosystem can be divided into two classes, irrigated wet season (WS) area and irrigated dry season (DS) area. In the irrigated WS area rainfall is supplemented by irrigation, as and when needed. Solar irradiance is reduced due to frequent cloud cover and yields are relatively low (4–5 t ha^{-1}). In an irrigated DS area, the rice crop is fully dependent on irrigation as rainfall is low. Solar irradiance is high, and yields are high – around 8 t ha^{-1} or more.

Based on grain yield, the irrigated rice ecosystem is divided into 3 zones: There is a high yield zone with mean yields > 5 t ha^{-1} (Australia, People's Republic of China, Indonesia, Japan and Vietnam); a medium yield zone with 4–5 t ha^{-1} (India, Malaysia, Philippines, and Thailand); and a low yield zone with < 4 t ha^{-1} (Cambodia, Laos, Myanmar, Nepal and Pakistan).

Irrigated rice is grown as a monoculture crop (e.g. rice-rice, rice-rice-rice, rice-rice-fallow), or in rotation with other crops, viz., rice-wheat, rice-legumes, rice-maize-legumes, rice-potato, rice-mustard, rice-vegetables, etc. Also, the cropping intensity varies from one crop per year (temperate rice as in Australia, northern People's Republic of China, Japan, South Korea, and North Vietnam) to two or three crops per year (in the tropical regions). Availability of water for irrigation determines the length of fallow periods between crops, which range from a few days to 3 months.

Irrigated rice is cultivated in bunded fields with good water control. Soil is mostly puddled and levelled, seedlings can be transplanted or sprouted rice seed can be direct wet-seeded. A shallow level of water is maintained during the crop growth period. Currently, most irrigated rice systems are highly mechanised, and high rates of fertilisers are applied to increase productivity. Insecticides are also applied to control insect pests, fungicides to arrest fungal diseases, and herbicides to control weeds.

Mostly, high yielding, semi-dwarf indica or japonica rice varieties are planted on irrigated rice lands in Asia. High yielding (10–15%) hybrid rice varieties occupy > 30% of the irrigated rice lands in People's Republic of China (2014) and smaller areas in other Asian countries. Although medium to low in their yield potential, high value aromatic rice varieties like basmati are grown in India and Pakistan while jasmine rice varieties are popular in Thailand and neighbouring countries. These aromatic rice varieties are mainly exported to the Middle East, Europe, and the USA.

Production constraints of the irrigated rice system include: poor management of inputs and unbalanced application of nutrients, unstable yield due to pest pressure, poor land levelling and/or irrigation water management, and environmental degradation due to excessive use or misuse of inputs. There can also be inadequate drainage (leading to salinity and alkalinity), and difficulty in sustaining high yields in what is currently managed as a chemical-intensive cropping system.

Other challenges which irrigated rice farmers' face in Asia are static or declining rice yields in intensive rice cropping systems. These are probably due to depletion of certain nutrients (P, K, Si, and Zn) in the soil, a decrease in soil organic matter content, the development of soil salinity and or alkalinity due to poor irrigation systems (without adequate drainage). Other causes of declining rice yields include the accumulation of toxic substances [iron (Fe), manganese (Mn), aluminium (Al) and arsenic (As)] in the irrigated soils due to short and/or wet fallow periods between crops, and poor rice field drainage. Arsenic toxicity is also increasing in areas where groundwater is pumped for irrigation from deep soil horizons containing arsenic-containing minerals, i.e. in eastern India and Bangladesh.

Small holder rice farmers are also being increasingly affected by changing climate (declining and poorly distributed rainfall, unpredictable droughts and floods, and destructive tropical cyclones). Socially, rice farmers face increasing production costs (due to higher wages and rising cost of inputs) and declining profits in their intensive rice farming, as well as a decline in government support (policy and institutional) available to farmers in general, and rice farmers in particular.

3.1.2. Rainfed lowland rice ecosystems

The rainfed lowland rice (RLR) ecosystem is one which is characterised by level to slightly sloping, bunded fields, fields which have a non-continuous flooding. The rice crop is established by direct seeding or transplanting of rice seedlings. Generally, one rice crop is rotated with a suitable other (non-rice) crop, though this depends on the length of the rainy season and availability of water for supplementary irrigation.

In Asia, the rainfed lowland rice ecosystem covers an area of about 45 mha (30% of the global physical rice area of 150 mha and 34% of the Asian rice area of 132 mha) [5]. Appreciable areas of the rainfed lowland rice ecosystems are located in India (16.1 mha), Thailand (8.2 mha), Bangladesh (5.1 mha), Indonesia (4.0 mha), Vietnam (2.9 mha), Myanmar (2.4 mha), People's Republic of China (1.8 mha), Cambodia (1.6 mha), and the Philippines (1.3 mha).

Based on their location on the 'topo sequence', [3] recognised three types of rainfed lowland rice ecosystems: shallow rainfed lowlands on upper terraces, intermediate rainfed lowlands occurring on medium elevation terraces and usually on flood plains near large rivers, and deep rainfed lowlands on lower terraces and in the valley bottom (Fig. 2.3). On upper terraces, a low soil profile depth and coarse soil texture contribute to low water and poor nutrient holding capacities and the soils generally possess a low level of indigenous soil fertility. This situation is aggravated by water movement down the slope, which reduces the availability of soil moisture supply, and erodes surface soil, thereby leaching the nutrients to down slope soils. On medium elevation terraces, water and nutrient losses to lower terraces tends to be balanced by input from upper slopes. On lower terraces and in the valley bottoms, the water table is nearer to the crop rooting zone, and soils are fine textured and enriched with organic matter and nutrients originating from the higher elevation slopes. As a result of these 'resource gradients', higher drought risks and nutrient limitations affect rice crops on upper terraces, while submergence risks are high for the lower terraces and valley bottoms due to runoff from upper slopes. Water accumulation in lower terraces will enable/impose an earlier crop establishment, though it may also delay crop harvests. Weeds are serious problems on upper terraces due to shorter duration of flooding, while they are better suppressed by floodwater in lower fields. With both droughts and floods being common in many of the rainfed lowland rice ecosystems, four sub-ecosystems can be categorised: favourable rainfed, drought prone, submergence prone, and both drought and submergence prone.

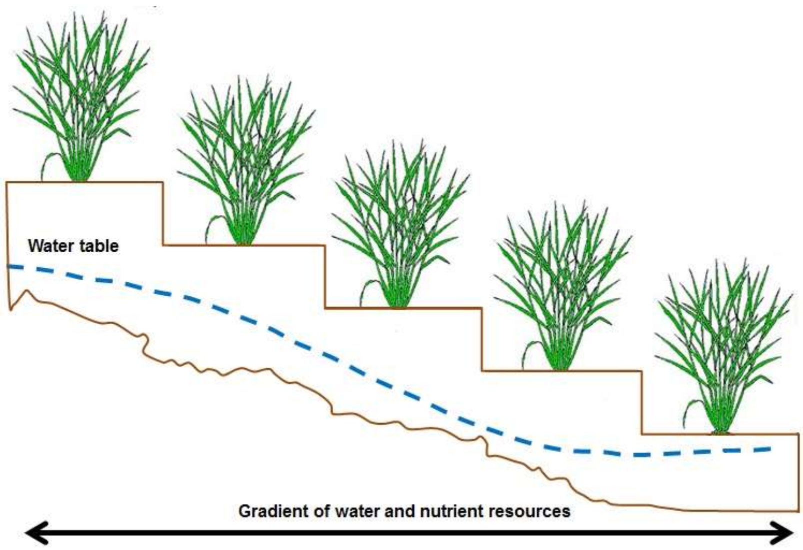


FIG. 3.3. Scematic diagrame of rainfed lowland rice ecosystems located on an undulating landscape (topo sequence) in Asia [3].

Overall, abiotic stresses are the most limiting constraints for an intensification of rice cropping and the improvement of rice yields in rainfed lowland rice ecosystems. Drought stress affects rice productivity on 19 to 23 mha of rainfed lowlands [6]. Floods are a serious problem, affecting about 11 mha of rainfed lowlands (shallow water depth flooding), with another 11.6 mha of rainfed lowlands being affected by intermediate water depth flooding [7]. It is important to note that actual areas affected by droughts and floods vary widely from year to year, and from country to country, due to highly variable local weather conditions. Another factor that affects rainfed lowland rice is soil quality [5]. It is estimated that about 7% of the rainfed lowland rice is grown on problem soils, such as acid sulphate or saline soils.

Thus, one third of the rainfed lowland rice is cultivated on relatively fertile soils, slightly less than one third of rice is planted on soils with low inherent fertility, and slightly more than one third of rice is grown on soils which possess one or more of the multiple soil constraints that are common to Southeast Asia.

Other production constraints include: pests, weeds, inconsistent yield, use of 'traditional' low-yielding rice varieties, and lack of suitable production technologies.

Two key strategies to manage drought in rainfed rice fields are: (a) drought avoidance and (b) drought moderation [3].

Drought avoidance

The first option to get a rice crop through periods of drought is to make water available for supplementary irrigation. This is accomplished through the digging of communal or individual farm ponds and the harvesting of rainwater, or by digging bore wells [8, 9]. This allows irrigation of the crop as and when needed. The second option is to avoid drought. Specifically, for areas with a stable climate which usually includes early or late season drought, the planting of rice varieties with a short growing season requirement, and/or the planting of drought tolerant varieties is accomplished. These varieties fit in with the local rainfall pattern and available crop growing duration.

Unfortunately, some farmers make compromises, and hold off on choosing early maturing drought resistant rice varieties because of their preference for other traits like consumer acceptance, taste, marketability and price. Thus, farmers all too often plant the popular, long duration varieties like Mahsuri and Swarna in South Asia, KDML 105 in Thailand and neighbouring countries, and traditional rice varieties in Cambodia and Laos. Because of these compromises by farmers, rice breeders are recommended to incorporate short duration and drought tolerance into rice varieties which possess the other traits that meet targeted consumer or market preferences. In addition to the above problems, there is a poor availability of seed of 'improved' varieties which have short growth duration and are drought tolerant – especially in Cambodia, and Laos.

The third option is to increase the roots' access to groundwater. This can be accomplished by deep ploughing (to break the hardpan below the plough layer), which will facilitate a deeper root growth, thereby allowing for absorption of water from the subsoil. Unfortunately, deep ploughing also increases the likelihood that all of the subsequent rains will penetrate deep into the ground, without allowing for an initial flooding of the rice fields.

Drought moderation

Moderation of drought is possible by two means: (a) direct seeding and (b) improved nutrient management.

Direct seeding: Dry direct seeding (DDS) on dry soil is the most preferred method, because dry seeds sown before the start of the rains germinate and grow only when the rains begin, thus fully utilising the early rains. Compare this with sowing dry seeds on moist soil. This latter method will require 112 mm of cumulative rainfall. In contrast, transplanting of rice seedlings on puddled soil will require 500 mm of rainfall. The DDS method for conditions of dry soil usually allows growth to begin 15 days earlier than DDS onto moist soil, and DDS on dry soil is 60 days ahead of transplanting. Rice crops established by DDS on dry soil also suffers less from water deficit because the crop uses the rainfall more efficiently. In fact, DDS on dry soil produced the highest yields across five years (from 1995–96 to 2000–01) in eastern India. A further benefit was that only DDS on dry soil permitted a 2nd crop of chickpea after rice harvesting during the moderate drought year of 1999. Other advantages of DDS include deeper, finer and more extensive root development of the rice plant and it also reduces labour needs for crop establishment. All that said, there are negative aspects to DDS. These include deep percolation (below the root zone) of rainwater due to absence of puddling, risks of poor germination, a poor crop stand due to dry spells soon after seeding, and a higher infestation of weeds due to simultaneous germination and growth of weeds together with the germinating rice seeds. The above are very important constraints to the use of direct dry seeding methods. Careful management is thus critical for successful crop establishment and early crop care and this includes effective weed control to ensure high and stable yields from DDS rice crops [10].

Soil nutrient status and early crop care: A low soil nutrient status is also an aggravating factor when drought stress occurs in rainfed rice crops [11]. Increasing the soil organic matter content is the key to improving soil fertility and soil water holding capacity, while a balanced application of nutrients will enhance crop growth and productivity. An integrated nutrient management approach is one which promotes the combined use of crop residues/composts/organic manures and chemical fertilisers to supply the nutrients required for reaching the targeted yield. In addition, early vigorous growth of rice seedlings (due to fertile soils) will allow a plant canopy cover to develop more quickly, which in turn will help reduce the evaporative loss of water from the soil surface. Further, surface mulching, which will help conserve soil moisture, is practical in unpuddled, direct-seeded rice fields. In well-watered rice crops, it is estimated that about 30% of seasonal evapotranspiration is evaporation from the soil surface, with 70% being transpired by the rice plants. Any changes in this ratio, even small ones, can adversely affect rice grain yields [12]. An adequate application of fertiliser was shown earlier to reduce soil moisture evaporation from 41 to 29%, while increasing rice grain yield from 2.1 to 4.8 t ha^{-1} [13]. In this study the high evaporation which occurred from the unfertilised treatment was caused mainly by a slow and incomplete closure of the crop canopy, an event which is commonly observed in many rainfed lowland rice fields of Asia. The improved crop growth leads to a decreased evaporation from the soil, relative to an increased transpiration through the plant. This phenomenon is called ‘vapour shift’, and it is considered to be one of the main mechanisms for improving crop yields and soil/crop water use efficiency in drought prone areas [14].

Interactions of soil moisture with nutrients have not been well studied and are poorly understood in rainfed lowland rice cropping systems. Hence, the potential risks of fertiliser applications to rice crops in water-limited soil environments are not well assessed and are thus uncertain [3]. This is the main reason why farmers in drought-prone areas hesitate to apply adequate fertilisers to rainfed rice crops unless there is water available, via supplementary irrigation, to alleviate crop water stress.

3.2. VARIETAL SELECTION

A number of rice varieties are grown in Asia to meet different culinary needs and tastes. Rice grain will undergo different pre-treatments and milling techniques in order to produce different types of rice products.

Based on appearance and level of milling, one can broadly classify three kinds of rice: 'rough' or 'paddy' rice (un-milled whole grain with hull and bran intact), brown rice (milled just enough to remove the husk, but not the bran), and white polished rice (milled to remove both hull and bran and then polished – the least nutritious rice). As to pre-treatment before milling, two types of rice are produced: raw rice (no pre-treatment prior to milling) and parboiled rice (rough rice partially cooked in hot water or steamed under pressure and then dried before milling).

Based on grain size and shape, there are four types of rice, long slender grain (most popular), medium grain, short bulky grain, and small fine grain (looks like cumin seeds). Based on aroma, there are two types of rice: aromatic and non-aromatic. Based on the level of stickiness (or amylose content), three types of rice are recognised: sticky (a glutinous rice variety as found in Laos and Thailand), low to medium sticky (jasmine rice, japonica rice), and non-sticky (the most common rice type, with long, medium or short grains, basmati rice). Thus, grain size and colour, texture and flavour/aroma when cooked, suitability for specific local or regional dishes; pre-treatments before milling and storability or shelf life after milling are all factors that determine consumer preferences for milled rice. Below are some examples of rice types which are popular in Asian countries:

Non-aromatic white long grain rice: This is one of the most popular, but least nutritious types of rice consumed worldwide, likely because it has a subtle flavour, one which perfectly complements both rich and delicate sauces. When it is milled to remove the husk and all the bran layer, most of the minerals, vitamins (80% of thiamine or vitamin B1), and fibre, which are found in the bran layer are lost, with only carbohydrate being retained. An additional loss of vitamin B1 occurs with a pre-cook rinsing followed by boiling of the milled rice. The milled long grain rice is slim and 4–5 times as long as it is wide. On cooking, the grains separate to give an attractive fluffy effect. It is extremely versatile grain type and is used for all rice based dishes including Chinese rice preparations.

Medium long and short bulky white rice: Commonly consumed by the poor in developing Asian countries, it is the key to national food security. All modern short growth duration, high yielding rice varieties, and most hybrid rice varieties, are bred to produce this type of rice which currently feeds billions of people in Asia, and elsewhere.

Parboiled rice: The rough rice is partially cooked in hot water or steamed under pressure and then dried before milling. This process hardens the grain, increases the whole grain (head rice) recovery, and reduces protein loss during the milling process. Parboiling also reduces the possibility of over cooking, helps to retain much of the vitamins and minerals (which diffuse into the endosperm during the parboiling process), and are thus not completely removed when the bran layer is later removed by milling. Parboiled rice also has a slightly 'fuller' flavour than milled raw white rice. Specific rice varieties (e.g. IR-20) are preferred for parboiling, followed by the making of popular preparations of '*idly*' (steamed rice cake) and '*dosa*' (flat, very thin pan cake like or crêpe like preparation) in south India. Parboiled basmati rice is thus more nutritious than raw white basmati rice, while brown basmati rice is the most nutritious of all, but possesses the shortest shelf life.

Brown rice: Brown rice undergoes only minimal milling, which removes the husk but retains the bran layer. Due to this, this type of rice retains more vitamin, mineral and fibre contents than regular or easy cook white rice. The grains remain separate when cooked, and the cooked brown rice has a distinctly nutty flavour and a chewy texture, which many people enjoy. Despite it being more nutritious than white polished rice, brown rice is less popular among consumers because it takes more time and fuel for cooking, it may cause digestive disorders in some people, and the oil in the bran layer tends to turn rancid during storage even at moderate temperatures (thus resulting in a short shelf life).

Aromatic rice types: These rice types contain a natural aromatic ingredient, 2-acetyl 1-pyroline, which is responsible for their fragrant taste and aroma. The fragrant quality of aromatic rice can differ from one year's harvest to the next, much like wine. The finest aromatic rice is aged this brings out an even stronger aroma.
Three types of aromatic rice are found: (a) Basmati rice – a very long, slender grained aromatic rice, grown mainly in the foothills of the Himalayas in India and Pakistan. It has a fragrant flavour and aroma and is the rice used in many north Indian and Pakistani dishes. The grains are separate and fluffy when cooked. Easy cook basmati, steam parboiled basmati, and brown rice basmati are also available. Brown basmati rice has higher fibre content and an even stronger aroma than white basmati. (b) Jasmine rice – it has long and slender grains that remain separate on cooking, but it differs from basmati rice in that it has a soft and slightly sticky texture when cooked. This is the most popular export variety of Thailand. (c) Very Fine grain aromatic rice: very tiny, short grain types that are popular in specific locations or regions (e.g. '*Kitchili samba*', GEB-24 in South India; '*Kalijira*' in Bangladesh). These rice types are used in locally important special rice dishes.

Japonica rice: It has short and medium length grains with low to medium amylose content (5 to 15% amylose). Grown mainly in Japan and California in USA, Japonica rice comes in a variety of colours including red, brown and black. When cooked, this rice has soft fluffy texture, glossy appearance, and excellent expansibility. It's used in Japanese and Caribbean cuisines due to its characteristic clingy, moist and firm nature when cooked.

Specialty rice – Glutinous rice: Glutinous and pudding rice is particularly suited to use in ethnic cuisines. These are often grown, cooked and eaten in the same locations (e.g. Laos and Thailand). Other specialty rice types are: Risotto rice (Italy) and aromatic rice as discussed above. Many of these specialty rice varieties have been central to a geographical region's livelihood and 'physical' survival.

Farmers in different parts of Asia have thus developed, and exchanged with other farmers, a number of rice varieties that will cater to a wide variety of culinary needs and food preferences. On the other hand, agricultural scientists have focused on developing mostly short growth duration, high yielding semi dwarf indica or japonica rice varieties – in order to meet the fast growing demand for food by the growing Asian and global populations. High yielding hybrid rice remains an important part of the international strategy to ensure food security. As of 2014, hybrid rice varieties occupy > 30% of the irrigated rice lands in People's Republic of China and smaller areas in other Asian countries.

Although medium to low in yield potential, and longer in growth period duration (140–150 days), high value aromatic and other specialty rice varieties like basmati are still grown in India and Pakistan, while jasmine rice and glutinous rice varieties are popular in Thailand and neighbouring countries. Both basmati rice and jasmine rice are the varieties which are mainly exported to the Middle East, Europe and USA.

Rice breeders focus on high yields, adaptability to different agro-climatic zones, responsiveness to fertilisers, resistance or tolerance to insect pests and diseases, competitiveness with weeds, tolerance to abiotic stresses (such as drought, flood, cold, heat; soil stresses: salinity, alkalinity, acid sulphate, acid peat, iron toxicity, low fertility). Breeders are also concerned with resilience to climate change, and screen for special cases of nutrition quality (high iron and high zinc rice).

In contrast, farmers look at plant type, growth period duration, grain type and quality, taste, and consumer preferences in local, regional, national, and even distant global markets. It is for these reasons that there is a local adaptation of new, improved rice varieties, one which is accomplished in close collaboration with farmers. To ensure that close collaboration of the farmers and breeders actually takes place, farmer participatory variety selection (PVS) trials have been initiated. These PVS trials are being designed and conducted at thousands of locations which represent the different rice growing environments in all important agro-climatic zones.

3.2.1. Facilitating the choice of appropriate rice varieties by farmers

This section describes how farmers facilitate appropriate rice varieties for uniform crop establishment and increased crop production.

- Incorporate farmer preferred varietal traits in all rice breeding programmes.
- Initiate farmer participatory variety selection (PVS) trials in order to identify farmer preferred improved rice varieties for each individual country's different regions.
- For dry season irrigated rice, farmers prefer varieties of medium plant height (115–125 cm) with strong stems to avoid lodging by heavy rains. The varieties have long panicles with many grains (which provide a higher crop yield), and a grain quality that yields a soft and fluffy texture after cooking.
- Farmers also prefer rice varieties with panicles located well below the flag leaves, a morphology that helps to reduce bird predation.
- For wet season rainfed and irrigated rice ecosystems, varieties with high rates of tillering and a larger number of heavy panicles are preferred. These varieties are high yielding, long grain types, ones which also yield a soft and fluffy texture after cooking.
- Based on their selection by farmers in PVS trials, a number of farmer preferred improved rice varieties, selected for different countries, are listed in Table 2. Please note that, for large countries like India or People's Republic of China, only a small sample of the most important varieties is given (for the full list of rice varieties, the reader can refer to national variety release publications).

TABLE 3.2. A LIST OF IMPROVED HIGH-YIELDING VARIETIES (HYVs), HIGH VALUE AROMATIC RICE VARIETIES, SPECIAL GLUTINOUS AND MEDICINAL RICE VARIETIES CULTIVATED IN SELECTED ASIAN COUNTRIES

Country	Popular farmer-preferred rice varieties			
	HYVs	Hybrids	Aromatic rice	Special types (e.g. glutinous, medicinal rice)
People's Republic of China	Golden Shuttle 1, Zhongyu 1, 4, 6 and 49 super rice varieties	Shanyou 2, Welyou 6, and three line hybrids	-	-
India (Different states have their own HYVs and hybrids bred by State Agricultural Universities and private sector seed companies)	IR 8, 20, 50, 64 & IR36 & 42 (tolerant to soil stresses); Himalaya 1 & 2 (cold tolerant); Ponni rice, Sona Mahsuri, Jaya, PTB 36 to 38, CR 1009, Saket 4, Rasi, Sasya Sree, TKM 9 & 10, ADT 36 to 39, 45, 48, & 51; Pusa 169, 205, 44, 834, 677; ASD16 to 20, PR 109, MDU 3 to 5; Annada, ND 118, Lalat, CSR 10, Gayatri, CST 7-1, Karjat 2 & 3, RP Bio 226 (Bacterial leaf blight or BLB resistant Samba Mahsuri), MTU 1075, UPR 2870, and 400 new rice varieties	APHR 1 & 2, KRH 1 & 2, DRRH 2 & 3, CORH 3 & 4, ADTRH 1, PHB 71, Sahyadri 1 to 4, PA 6129, 6201 & Ariz 6444 Gold, Pusa RH 10, PRH 122R, JRH 8, Suruchi 5401, NK 5251, CRHR 32, CR Dhan 701, US 305 & 314, 27P52, RH1531, Hybrid 6201; Hybrid basmati RH10	Basmati 370, 385, & 386; 1121 Extra Long Grain Basmati, D-98 and a hybrid variety Pusa Basmati-1 & Pusa 1460, Haryana Basmati, & Hybrid basmati RH10; '*Kitchili Samba*', '*Kalijira*'	-
Indonesia	Tjina, Tanjung, Wulu, Peta, Siherang, IR 20, 26, 28, 30, 32, 34, 36, 38 & 64; TSR 4, Inpago 4, Inpara 4, Aek Sibundong; plus 10 new HYVs being developed from Acehnese rice lines	Hipa 12 SBU Hybrid; Hipa 5 Seav Hybrid	Cianjur Pandanwangi, Rajalele, Acehnese rice,	-
Bangladesh	Balam Dhan & Shail Dhan (*aman* rice); flood tolerant BRRI Dhan 51 (Swarna-Sub1) & 52 (BR 11-Sub1); BINA Dhan 7 (short growth period duration to escape drought);	-	*Kalijira*	-
Vietnam	OM6L, OM70L, OM31L (waxy), OM6162, OM6976; Cantho 2 & 3; VND95-20 (salinity tolerant); VND99-3 (one of 8 mutant rice varieties); 70 CLRRI-developed HYVs; IR64	Chinese hybrid rice varieties in north Vietnam	B-16; Jasmine 85; OM4900, OM5451, OM7437	-
Thailand	RD 6 & 8; RD 19 & sister lines (flood tolerant); Brown rice, Red cargo rice; IR53650 (flood tolerant; acid sulfate soil tolerant with some liming)	-	KDML 105	Black & white glutinous rice

Myanmar	Nga Kywe, Kauk Hnyin, Khao lines, Yangon Saba, Paw San, Emata, Loonzain, Nagasein	-	Pearl Paw San; Zeera rice (very fine grains)	-
Philippines	Angelika, Ifugao rice, IR 64 & 841, Milagrosa Pino, Sambaguita, Sinandomeng, Wag, V 10 & 160; PSB Rc82, Tubigan, and 80 new varieties	-	Mabango (NSIC Rc128)	Malagkit 1, 2, 3 & 4 (NSIC Rc13, NSIC Rc15, NSIC Rc17 & NSIC Rc19)
Japan	Kirara 397, Koshihikari, Sasanishiki, Asahi	-	-	-
Cambodia	Neang Minh, Neang Khon		Cammalis, Phka Kheni, Phka Malis	Red rice
Pakistan	DR 82 83, KSK 133 & 434, PK 386, PS 2, and IR 6 & 9	-	PK 385, 1121 Extra Long Grain Basmati, D-98, Super Basmati	-
South Korea	Tongil & sister lines (Indica x Japonica hybrids; cold-tolerant);	-	-	Haiami, Yeongan, Heugkwang, Heugjinju, Geonganghongmi (medicinal, rich in antioxidantsroperties) ; Keunnun & Samkwang (brown rice, medicinal); Milyang 236 (reduces BP), Goami 2 & 3 (diabetic rice)
Sri Lanka	Keeri Samba, Supiri Nadu, Supiri Samba,	-	-	Sri Lankan Red Rice
Nepal	Himali & Kanchan (cold tolerant)	-	-	
Lao PDR	North: TDK6, NTH1, NTN1, People's Republic of China, PNG2, PNG3, PNG6; Central: TDK1, TDK3, TDK6, TSN1, TSN3, TSN4, PNG2 & PNG5; South: TDK1, TDK6, TSN2, PNG6 (medium growth period duration). TDK4 , TDK10, TDKsub1 (flood-tolerant), RD6 & RD8 (long duration)		KDML 105	Chao Deng, ILoup, Black rice
Malaysia	MR 219 & 220 (most popular); MR185; MR220 CL1 & CCL2 (resistant to herbicides); MR 253 & 263 (for acid peat soil); Padi Jaya, Padi Masira, Padi Sri Malaysia Dua/Satu, PH 9, Sri Malaysia II	Siraj (Indica x Japonica cross)	Jasmine or Basmati type (for rainfed lowlands)	-

Taiwan, China	TNG 67, Taikeng 8 (Japonica); plus 39 japonica varieties, 3 indica varieties, 8 japonica waxy varieties, 3 indica waxy varieties	-	Tainung 74	-
Australia	Amaru, Jarrah, Reiziq, Doongara, Koshihikari, Langi, Opus,	-	Kyeema	-

Data Sources: [2, 15]

3.3. SEED HEALTH AND SEED QUALITY MANAGEMENT

This section describes using high quality seed for uniform crop establishment. Specific directions are provided on how farmers can best develop ‘nurseries’ for raising rice seedlings for transplanting, and how to prepare the main field prior to transplanting young rice seedlings.

3.3.1. Good quality and healthy seed

Good quality seed is the starting point for production of improved rice varieties. This section describes how farmers can either buy high quality seed, or produce and use their own good quality seed.

- Seeds of improved varieties are pure (of a single variety), clean (no impurities), free from infestation by insect pests and/or fungal pathogens, and healthy (full, large grains of the same color and size, and with no cracks) (Fig. 4).
- Planting clean seeds of good quality results in fewer seeds being used, gives more uniform germination and yields more vigorous seedlings. It also reduces the need for replanting, results in fewer weeds and gives 5–20% higher crop yields.
- Farmers need to renew their seeds by purchasing high quality seeds at least once in 3 years in order to maintain varietal purity and high seed vigor. Currently, there are not enough high quality seeds available in many developing countries of Asia (e.g. Cambodia, Laos, Myanmar and Nepal).

FIG. 3.4. Good quality seed is the starting point for establishing healthy, robust rice crops, ones which have high grain yields and thus increase the profits earned by the rice farmer.

3.3.2. How farmers can test rice seed germination and measure seedling emergence from the soil

This section describes how farmers can test their own seed to ensure optimum germination for uniform crop establishment and growth.

- Place 100 rice seeds in a tray which contains a 1 cm layer of soil;
- Keep the soil moist by sprinkling water and observe the rate of germination. Note: larger seeds tend to germinate faster than smaller seeds;
- Count the total number of seedlings after seven days. Good quality seeds will show greater than 70% germination and have complete seedling emergence.

3.3.3. How farmers can produce their own good seed

This section describes how farmers can produce their own seed to minimise farm cost.

- A dry season irrigated rice crop is the best for farmers to produce their own good seed.
- Choose a field with well drained, fertile soil, one which has a low risk for both flooding and drought.
- Plant good quality clean seeds in a well prepared, weed-free nursery in order to produce healthy and robust seedlings for use in transplanting.
- Prepare the main rice field well: plow, puddle and level it as a way to help control weeds and improve water management.
- Choose young (15–20 days old) healthy seedlings and plant two seedlings per hill, using 22.5 cm x 22.5 cm spacing between hills.
- Manage the rice crop well during its development (see Sections 2.5, 2.6, 2.7 and 2.8).
- Rogue (remove) some of the odd or abnormal rice plants in order to get a uniform looking crop at the flowering stage. To accomplish this, remove all atypical plants, e.g. remove plants that differ (from the majority of plants in the field) in height, leaf color, flowering time, panicle type, and/or grain shape and size. Also remove insect damaged and pathogen infected plants, as well as plants which have dirty or damaged panicles.
- Harvest the rice crop at maturity, i.e. when 80–85% of the grains are straw colored and the grains are hard when you bite them.
- Thresh, clean and dry the seed quickly. After harvest, grade and label the seed properly.
- Store the labelled, dry seed in clean, sealed (air tight) containers which are placed in a cool (< 20ºC), dry (Relative Humidity < 40%), and clean place, ideally inside the house.

3.4. LAND PREPARATION

Land preparation and planting of seedlings is necessary in order to take full advantage of the growing season and thus obtain high yields. Appropriate mechanization will help farmers to carry out all farming operations, including efficient land preparation in a timely manner.

Rice fields can be prepared in three different ways: (3.4.1) puddling to turn the surface soil to mud, (3.4.2) unpuddled aerobic soil cultivation and levelling, and (3.4.3) raised bed land preparation.

3.4.1. Puddling to turn the surface soil to mud

This is the most common method farmers use to puddle the soil and turn it to mud prior to transplanting young rice seedlings. This is the most common and generally the best practice for low lying lands which are likely to get flooded during the rainy season.

- Animal or hand pulled tractors, or a four wheel motorised tractor, can be used for land preparation.
- Spread out residues from the previous crop and then incorporate these residues and/or organic manure and compost, during the first plowing.
- Then irrigate the field and allow 15 days for weed seeds to germinate and for organic matter to decompose.
- Apply (broadcast uniformly) a phosphorus fertiliser, and also make the first application of a potassium fertiliser. Do this prior to the 2^{nd} ploughing.
- Plough the 2^{nd} time to uproot all germinated weeds and to incorporte P and K fertilisers. Then puddle the soil and level the field by using a thin film of water (Fig. 5). Field levelling is very important for obtaining a good germination of seeds, or a uniform establishment of transplanted seedlings. The objective is to get vigorous early growth (aim for full canopy development to assist in suppression of weeds), and a water efficient irrigation.
- Repair and reshape field bunds and plug or destroy all rat holes to minimise rat damage during seedling growth and grain filling periods.

(a) (b) (c)

FIG. 3.5. Land preparation by puddling and levelling in a flooded field: (a) Levelling with an animal-drawn leveller; (b) Levelling by hand-tractor-drawn leveller; (c) Puddled and levelled field ready for transplanting (Source: www.knowledgebank.irri.org/).

3.4.2. Unpuddled aerobic soil cultivation and levelling

The methods are similar to preparing land for crops like maize, soybean or wheat. The details are as follows:

- An animal drawn plough, a hand held tractor, or a four wheel motorised tractor can be used for land preparation. Till the field when the soil is moist and friable (Fig. 3.6a).
- Spread out and incorporate into the soil all residues from the previous crop and the weeds that have grown during the fallow period. In addition, farmers can apply organic manure and or compost and incorporate it into the soil during the first plowing.
- After the first plowing, the fields will appear rough with large clods (Fig. 3.6b).
- Wait for the first rain, or irrigate the field (if possible) and allow 15 days for weed seeds to germinate and for organic matter to decompose in moist soil.
- Apply (broadcast uniformly) a phosphorus fertiliser, and also make the first application of a potassium fertiliser prior to the 2nd plowing.
- Plough for 2nd time to uproot the germinated weeds, then harrow and finally level the soil under dry condition to get a smooth seedbed (Fig. 3.6c).
- Alternatively, a tractor with an attached rotovator is used to till and level the soil (Fig. 3.6d). Field levelling is very important for obtaining a good germination of seeds and a uniform emergence of seedlings throughout the field. The objective is to get vigorous early growth (aim for full canopy development to assist in suppression of weeds), and water efficient irrigation.
- Repair and reshape field bunds and plug or destroy all rat holes to minimise rat damage during seedling growth and grain filling periods.

(a) (b) (c) (d)

FIG. 3.6. Dry land preparation: (a) First plowing; (b) Appearance of the soil with large clods just after primary tillage; (c) Well prepared dry soil after harrowing and levelling, ready for dry seeding; and (d) Using a rotovator for preparing dry or moist soil (Photos by V. Balasubramanian).

3.4.3. Raised bed land preparation – SRT (Saguna Rice Technique) method of cultivation of rice and other crops

100 cm wide raised beds are formed between 36 cm wide furrows for dibble sowing seeds of rice and other crops in rows. This is called Saguna Rice technique (SRT) and has been promoted in Thane, Raigad and Ratnagiri districts of Maharashtra State, India for more than 3

years by Mr. Chandrashekar Bhadsavle of Sagunabaug, Maharashtra, India [12]. The details of the SRT method are as follows:

- Prepare the land aerobically with one to two ploughings or one tillage with a rotovator, followed by one to two times each harrowing and levelling. Till the field when the soil is moist and friable.
- Mark long lines 136 cm apart along the natural slope of the field, with the help of a long twine or a rope (Fig. 3.7a).
- Use the furrow opener to make 36 cm wide furrows. Then use the soil from the furrows to make 100 cm wide raised beds between furrows and level the beds well (Fig. 3.7b, c).
- Make the furrows gently sloping along the natural slope of the field to help drain excess water, if necessary, during heavy rains.
- If irrigation is available, water is released into the furrows and allowed to move laterally to wet the beds. However, direct drip irrigation of the beds is usually the most water efficient method of irrigation.
- Once beds are formed, no tillage is practiced between crops and weeds are controlled by herbicides.
- Beds are reshaped by taking the excess soil from furrows and placing it uniformly on top of the beds once every year.

(a) (b) (c)

FIG. 3.7. Making raised beds and furrows in prepared field, Raigad, Maharashtra, India: (a) Marking lines to make furrows and beds, (b) making furrows and beds manually, and (c) making furrows and beds with furrow openers attached to a tractor (Photos by Chandrashekar Bhadsavle).

3.5. CROP ESTABLISHMENT

Proper establishment of the crops is critical for successful crop production. The aim is to get a uniform germination of seeds and a uniform crop emergence, along with early vigorous growth of the rice seedlings – all in order to develop an early and full canopy of plant cover over the soil to suppress weeds and to use all resources efficiently and evenly over the entire field. Once a good crop stand is achieved, further management of the crop becomes easier.

There are three methods of rice crop establishment: (i) transplanting rice seedlings; (ii) direct wet seeding of sprouted rice seeds, and (iii) direct dry seeding of dry rice seeds on flat land or on beds.

3.5.1. Rice (seedling) transplanting

This section describes step-wise procedures of raising seedlings in a nursery, followed by transplanting the seedlings onto the main field.

Seeding rates for the nursery:

20 to 30 kg of good quality seed can be sown into a nursery area of 200 to 300 m^2. This is adequate for producing enough high quality seedlings for transplanting into one hectare of the main rice field. (most farmers now use more than 50 kg of seeds for a 500 m^2 nursery area in order to produce enough transplants for one hectare). This current high rate of seed use for the nursery is likely because the seeds sown into the nursery bed are of poor quality.

Selecting good seeds:

Immerse the seeds in a bucket of water, stir well and remove all of the floating, unfilled, or damaged seeds. Also remove other impurities. The good seeds will sink to the bottom once stirring ceases. Separate these seeds and pre-germinate (sprout them immediately in a moist environment) for sowing into the nursery area.

Seed treatment:

Dry seeds are treated with fungicides or biocontrol agents to kill seed borne pathogens that cause root rot, seedling wilt, or seedling blast. Fungicides and bio inoculants are not compatible for simultneous seed treatment. Therefore, keep the fungicide treated seeds for a minimum of 24 hrs before inoculation with biofertilisers. Alternatively, seeds can be treated with biocontrol agents to prevent seed borne diseases. Biocontrol agents and bioinoculants are usually compatible for simultaneous seed treatment.

Fungicide seed treatment – Dry seed treatment:

Use half a teaspoon (2.5 g) of fungicide (e.g. Benylate + Mancozeb mix or Arazone red) to treat each one kg of dry seed as described below:

- Mix the fungicide with 5 ml water for each half of a teaspoon of fungicide by shaking the water + fungicide gently inside a plastic bag or a large plastic bottle.
- Distribute the fungicide (which will be in a slurry) about the walls of the plastic container.
- Place each 1 kg batch of dry seed in the plastic container, reseal, and then shake very gently in order to coat the seed uniformly with the fungicide slurry.
- Wait for 24 hrs before soaking the treated seed in water for obtaining pre-germination.
- Fungicide treated dry seeds can be stored for up to 30 days without any loss of seed viability for later sowing.

Fungicide seed treatment – Wet seed treatment:

- Mix half a teaspoon (2.5 g) of fungicide (e.g. carbendazim, pyroquilon, or trycyclozole) in one liter of water and add one kg of dry seed and then soak for 2 hrs.
- Drain off the fungicide solution and soak the seed in a new batch of water for sprouting as described below.
- Wet seed treatment with fungicides is more effective than dry seed treatment and it protects the seedlings against seed borne diseases for up to 40 days.

Seed treatment with biocontrol agents and biofertilisers:

- Mix biocontrol agents such as Trichoderma viride at one teaspoonful (4–5 g) per liter of water. For Pseudomonas florescens use 2 teaspoonsful (10 g) per liter of water and soak one kg of seed in the fungicide water emulsion for 12 hrs.
- As biocontrol agents are compatible with bofertiliser preparations, farmers can mix biocontrol agents and biofertilisers for simultaneous seed inoculation and seed treatment.
- Mix bioinoculants such as Azospirillum and or Phophobacteria (a culture of bacteria that solubilze soil P) using 2 teaspoonsful (10 g) of each bioinoculant per liter of water and soak one kg of seed in this mixture for 12 hrs.
- After 12 hrs, drain off the solution and keep the wet seeds covered with a gunny sack in a warm, dark place for 24 hrs to allow for seed germination (sprouting) as described below.

Techniques for pre-germination or sprouting of seeds:

- Pre-germinated seeds are often used for sowing into a nursery in order to produce seedlings for subsequent transplanting into the main rice field.
- Soak the seeds treated with fungicides or biocontrol agents in water for 12 hrs (overnight).
- Gibberellic acid application: Rice varieties with a slow germination rate and slow and/or variable emergence may respond favourably to treatment of the seed with the plant growth hormone, gibberellic acid (GA_3). Applications of the hormone significantly improve germination, emergence rate and seedling vigor for semi-dwarf varieties of long grain rice.
- Cover the wet seeds with a gunny sack and keep it in a warm, dark place for 24 hrs. At this time most of the seeds will have sprouted, e.g. the first root will have grown to 2–3 mm in length.
- Sprouted seeds are ready for sowing in nursery beds or sowing by direct wet seeding into the main field.

Rice nurseries:

Three types of rice nurseries are currently utilised.They include (a) flat wet bed rice nursery, (b) modified mat nursery, and (c) specially modified mat nursery (or tray nursery) for subsequent machine transplanting.

Flat wet bed rice nursery (commonly used)

The reduced area of the flat wet bed nursery uses less land than traditional nurseries and produces robust, healthy, and vigorous seedlings in 20–40 days. Vigorous seedlings which are produced in good nurseries using good quality seed (Fig. 3.8 a,b) will result in less replanting, have fewer problems with weeds, insects and diseases, and produce higher grain yields.

- Prepare 200 to 300 m^2 of a nursery area to raise the seedlings which will subsequently be planted on each one hectare (10000 m^2) of the main rice field. Choose a suitable spot in the field for the nursery area (preferably fenced), one which has good soil and good water availability, i.e. a nursery plot which is easy to irrigate and drain.
- Start the preparation of the nursery seedbed 3–4 weeks before the chosen time of transplanting the seedlings into the main field.
- Apply organic manure and/or fertiliser to the nursery plot, as needed, based on advice from the local extension officer.
- Prepare the nursery seedbed by plowing 2 or 3 times, level well, and make furrows at 1 m intervals to assist in the irrigating and draining of the seedbeds, as need be (Fig. 3.8c).
- Sow the pre-germinated seeds thinly and uniformly onto the soil of the seed bed. Then cover the soil with a thin layer of rice straw.
- Allow irrigation water to flow gently into the furrows to soak the seedbed soil. Water the nursery plot as and when needed in order to keep the soil moist. Protect the nursery from heavy rains during the first five days after sowing (DAS). This is accomplished by the timely draining of rainwater. At 7 DAS irrigate the nursery so as to maintain a 2–3 cm level of surface water on the seedbed soil.
- Seedlings are ready for transplanting 20 to 30 DAS for short growth duration varieties and 30–40 DAS for long growth duration varieties (Fig. 3.8 d).
- Remove the seedlings carefully from the nursery and bundle them for transport to the main field.

(a) (b) (c) (d)

FIG. 3.8. Rice nursery preparation, seeding and seedling management: (a) Good quality seed; (b) Sprouted seed; (c) Level seedbeds; and (d) Nursery with seedlings (Photos by V. Balasubramanian).

Modified mat nursery for rice

In a modified mat nursery (Fig. 3.9), seedlings are established in a layer of soil mix , arranged on a firm surface, one which will be impermeable to root growth. As a result, root damage is minimal while separating seedlings. Seedlings are ready for planting within 15–20 days after seeding (DAS) [16].

- *Seed required:* To plant 1 ha (with 1–2 seedlings per hill at 20 x 20 cm spacing), use 10–15 kg good quality seeds (with > 80% germination and establishment).
- *Preparing the nursery area:* Prepare 100 to 150 m^2 nursery area in order to plant 1 ha. Select a level area near the house and/or a water source. Spread a plastic sheet or banana leaves on marked area to prevent roots growing deep into soil.
- *Preparing soil mixture:* Four (4) m^3 of soil mix is needed for each 100 m^2 of nursery. Mix 70% soil + 20–25% well decomposed organic manure + 5–10% rice hulls (or ash from rice hulls). Incorporate into this soil mixture 1.5 kg of di-ammonium phosphate (or 2 kg 15–15–15 NPK fertiliser) for every 100 m^2 of nursery area.
- *Filling in soil mixture:* Place a wooden frame of 0.5 m long, 1 m wide and 4 cm deep divided into 4 equal segments on the plastic sheet or banana leaves. Fill the frame almost to the top with the soil mixture.
- *Sowing:* Sow the pre-germinated seeds uniformly at application rate of 100 g m^{-2} and cover them with dry soil.
- *Soaking the seedbed:* (a) Sprinkle water immediately from above to soak the bed. (b) Remove the wooden frame and continue the process (fill soil mix sow seed-cover seed water) until the required nursery bed area is completed.
- *Watering:* Water the nursery as and when needed to keep the soil moist. Protect the nursery from heavy rains for the first 5 DAS by timely drainage. At 7 DAS, maintain a 1 cm water level around the mats. Drain the water 2 days before lifting the seedling mats for transport to the main field for transplanting.
- *Spraying fertiliser solution* (optional): If seedling growth is slow, sprinkle a 0.5% urea + 0.5% zinc sulphate solution from above at 8–10 DAS.
- *Lifting seedling mats:* Seedlings reach sufficient height for planting in 15–20 DAS. Lift the intact seedling mats and take them to main field for transplanting.

(a) (b) (c) (d) (e) (f) (g) (h)

FIG. 3.9. Modified mat nursery [16]: (a) Marked level area with a plastic sheet (or banana leaves) spread over it; (b) Soil + manure + rice hull ash to prepare soil mix; (c) Filling wooden frame with prepared soil mix; (d) Sowing sprouted rice seeds and covering them with a thin layer of soil; (e) Moistening the seed bed with water by a rose can; (f) Lifting the wooden frame to continue the process until all required nursery beds are made; (g) Watering the seedbeds as and when necessary to keep the soil moist when seedlings start growing; and (h) Lifting the intact seedling mats for transport to the main field.

Special mat nursery (or tray nursery) for preparing seedling mats for machine transplanting

The special mat nursery is similar to the modified mat nursery as described above. Often seedling trays are used to prepare special seedling mats (Fig. 3.10) that are preferred for subsequent transplanting by machine (Fig. 3.11b). The details follow:

- Arrange the seedling trays on a firm surface. Each tray is 50 cm wide, 30 cm long and 2.5 to 3.0 cm deep.
- Prepare three (3) m^3 of soil mix for each 100 m^2 of tray nursery area. Mix 70% soil + 20–25% well-decomposed organic manure + 5–10% rice hulls (or ash from rice hulls). Incorporate into this soil mixture 1.2 kg of di-ammonium phosphate (or 1.4 kg 15–15–15 NPK fertiliser) for every 100 m^2 of tray nursery area.
- The putting of the soil mix into the trays, the sowing of sprouted seeds, followed by covering the sprouted seeds with dry soil, and then watering gently the seedling trays from above with a sprinkler can, as well as spraying the seedlings at 8–10 days after sowing with a 0.5% urea + 0.5% zinc sulfate solution (if needed) are all similar to procedures described in 6b above.
- The rice seedlings are then ready in 12 to 15 days for machine transplanting.

FIG. 3.10.Tray nursery:Seedling mats prepared in seedling trays for machine transplanting (Photo by V. Balasubramanian).

Transplanting rice seedlings from the nursery into the main field

- Handle the seedlings carefully so as to ensure their fast revival and rapid growth after transplanting.
- Transplant the seedlings into the puddled, levelled main field immediately after removing them from the nursery. Too long a delay in transplanting will lead to slow seedling revival, or even death of some seedlings.
- The seedlings are young when transplanted in order to get a rapid recovery and vigorous early growth. For example, 20 to 30 day old seedlings are best for the improved short growth duration varieties. Use 30 to 40 day old seedlings for long growth duration varieties. Avoid transplanting seedlings which are older than 40 days.
- Transplant 2 or 3 seedlings per hill from the flat wet bed nursery into the main field. Only 1–2 seedlngs per hill are required from the modified mat nursery. Seedlings are planted at a 1 to 2 cm depth. The plant to plant spacing in the main field is ranged from 20 x 20 cm to 25 x 25cm (Fig. 3.11a).
- Transplanting machine is used to transplant rice seedlings in rows at an inter row spacing of 30 cm (Fig. 3.11b).
- Alleys: Leave one alley for every ten rows to facilitate both irrigation and drainage (this is especially important for poorly drained soils).

(a) (b)

FIG. 3.11. Transplanting rice seedlings into the main field: (a) Manual transplanting in rows; (b) Transplanting by a machine into rows spaced 30 cm apart (using specially prepared seedling mats) (Photos by V. Balasubramanian).

3.6 DIRECT SEEDING OF RICE INTO THE MAIN FIELD

There are three methods for direct seeding of rice: wet, direct seeding, dry, direct seeding, and dibble seeding onto raised beds. Each method is briefly described below.

3.6.1. Wet, direct seeding of sprouted rice seeds onto puddled soil

Wet, direct seeding is the sowing of sprouted seeds onto puddled, levelled soil by broadcasting or by drilling in rows using a drum seeder. Wet, direct seeding has become a substitute for transplanting in response to rising wages and scarcity of labour at the time of transplanting. It can be used during the wet or dry seasons (preferably dry season) in areas with both good drainage and water control.

- General: Wet, direct seeding (or wet seeding) is the sowing of sprouted seeds onto the puddled, levelled soil of the main field. This is accomplished by broadcasting the pre germinated seed, or by 'drilling' the wet seed into rows using a drum seeder. The direct seeding method can be used in wet or dry season (preferably dry season) for main field areas with good drainage and good irrigation water control.
- Selection of rice varieties: Rice varieties with early seedling vigor, rapid growth, and a good ability to suppress weeds are preferred for use in wet seeding.
- Seeding rate: Use 60–80 kg ha^{-1} of good quality dry seed for sprouting and subsequent broadcasting. Use 40–50 kg ha^{-1} for sprouting and subsequent drum seeding in rows. The inter row (between row) spacing for drum seeding is 25 cm.
- Seed priming (optional for direct seeding): Soak the seeds in water for 12 hrs (overnight), drain the water and sprout the moist seeds (as detailed above) for immediate sowing. If seed sowing is delayed, dry the soaked seeds in the shade to about 12–14% moisture content. Then, store the dried seed in an air tight container for later planting. These soaked and then dried seeds are called 'Primed' seeds, and

they are 'thought' by some field researchers to produce crop plants that resist drought better.

- Good land preparation and levelling: Plough, harrow, puddle and level the land. After levelling the main field, construct furrows (alleys) at regular intervals to facilitate easy drainage of excess water (Fig. 3.12a).
- Sowing: Sow the sprouted seeds by broadcasting or using a drum seeder onto the puddled, levelled soil. The person sowing the seed walks backward (Fig. 3.12a, b) without making too many depressions in the field, e.g. to prevent water collecting in the depressions, which can rot the sprouted seeds.
- Gap filling: After 15 to 20 days judiciously observe the field. Carefully remove (uproot) some seedlings from areas which are too densely planted, and plant those uprooted seedlings into empty spaces in sparsely planted areas. This will give a near uniform distribution of plants.
- Careful water management. For the first 10–15 days after direct seeding (DAS), flush irrigate the field to keep the soil saturated, but not flooded, with water (Fig. 3.12c). Thereafter, maintain a water level of 2 to 5 cm until plant maturity. A shallow submergence in water generally promotes tillering, which can increase the final yield of grain per plant.

(a) (b) (c)

FIG. 3.12. Direct wet seeding of rice by broadcasting and row seeding with a drum seeder: (a) Broadcast sowing; (b) Drum seeding in rows; and (c) Row seeded rice crop (Photos by V. Balasubramanian).

3.6.2. Dry, direct seeding on aerobically prepared and levelled dry or moist soil

Dry, direct seeding (DDS) onto dry soil is preferred by farmers in drought prone areas. The best time for DDS is when there is a strong probability for sufficient rains to occur, within a week, to soak the soil. Dry seeds sown before the start of the rains germinate and grow quickly after early rains. Dry seeding on moist soil requires more than 100 mm cumulative rainfall before sowing can begin. DDS onto dry soil is 15 days earlier than DDS onto moist soil, and 60 days ahead of transplanting. Rice crop established by DDS onto dry soil suffered less from water deficit, apparently using the rainfall more efficiently. DDS onto dry soil produced the highest yields across 5 years (from 1995–96 to 2000–01) in eastern India. Also, use of DDS on dry soil permitted a 2nd crop of chickpea after rice harvesting during the moderate drought year of 1999–00. Other advantages of direct seeding include deeper, finer and more extensive root development and reduced labour need for crop establishment. However, there are risks. For example, too deep a percolation of rainwater due to absence of puddling, poor germination and a poor crop stand due to dry spells which occurred soon after seeding, and higher infestation of weeds due to simultaneous germination and growth of weeds along with germinating rice seeds. These can be important constraints on the use of direct seeding. Careful management is thus critical for successful crop establishment and early crop care (including effective weed control) in order to get high and stable yields from DDS rice crops [3].

Seed priming is considered useful for DDS. Seeds are soaked in water for 12 h just before direct seeding onto a field. If seeding is delayed, the soaked seeds can be dried in the shade and stored (see above) until it can be planted that season.

A Chinese-built hand tractor with a tiller, seeder and planking attachment is highly useful for row seeding onto dry or moist soil. A seed cum fertiliser drill is also available for dry seeding and fertilising at the same time.

Zero till rice is a subsystem of dry seeded rice. Here, fields are flush irrigated; weeds are allowed to germinate and are then killed by applying a non-selective herbicide such as glyphosate. A zero till seeder is then used to sow the rice seed in rows.

The details of dry direct seeding follow:

- Uniformly broadcast dry seeds or primed seeds at a rate of 80 to 120 kg ha^{-1} (Fig. 3.13a) onto the dry or moist soil.
- Harrow the field after broadcast seeding to lightly cover the seeds with soil, manually using a rake or by a tractor drawn rake (Fig. 3.13b).
- The depth of seeding is critical for upland rice. Seeding depth is determined by the seed size and the physical condition of the soil – smooth level seed bed with fine clods, soil bulk density, and soil moisture status. The optimum seeding depth is 1 cm to 2 or 3 cm for most upland rice varieties.
- Farmers can also sow the seeds behind a plow (Fig. 3.13c) or drill the seeds with a seed cum fertiliser drill (Fig. 3.13d) at a seed rate of 40 to 60 kg ha^{-1}, if they wish to plant in rows. The optimum row to row spacing is 20 to 25 cm.
- With sufficient early rains, seeds germinate and seedlings start to emerge from the ground. Optimum crop emergence is indicated when 333 seedlings emerge per square meter.
- Gap filling: Carefully observe the field for 15 to 20 DAS. If the field is flooded, carefully remove (uproot) some seedlings from areas which are too densely planted, and plant those uprooted seedlings into empty spaces in sparsely planted areas (Fig. 3.14). This will give a near uniform distribution of plants over the field.

(a) (b) (c) (d)

FIG. 3.13. (a) Dry direct seeding: Sowing seeds by broadcasting; (b) Harrowing to cover the seeds with soil; (c) Sowing the seeds behind a plough for seeding in rows; and (d) Seed cum fertiliser drill for dry drill seeding (Source: www.knowledgebank.irri.org/).

FIG. 3.14. Gap filling: Planting missing hills in direct broadcast seeded lowland rice fields, Vietnam [2]

3.6.3. Bed planting: Direct dibble seeding of dry rice seeds onto raised beds

One of the more successful methods of planting rice seeds onto beds is the Saguna Rice Technique (SRT) method which has been developed and promoted by Mr. Chandrshekar Hari Bhadsavle in Maharashtra State, India, since 2013. In this method, a 2nd crop of grain legumes, groundnut, or vegetables can be grown after rice harvesting for those beds with enough residual moisture in regions of longer rainfall duration. Wherever supplementary irrigation is available, a 3rd crop (sunflower or other non-rice crop) can be planted on the same bed. Once the beds are formed and the first crop is planted and harvested, zero tillage is practiced for the subsequent crops (of course, excess soil from the furrows is removed and placed uniformly on the beds once every year) and weeds are controlled by herbicides. Crop residues and crop roots left in beds decompose slowly and enrich the soil, thus adding to the vigorous growth and multiplication of soil microorganisms and other soil fauna like earthworms [17]. A search is ongoing to find a more suitable seed drill for direct seeding onto permanent beds where zero tillage is utilised.

More than 600 farmers have been trained in the SRT method and they are successfully adopting it to grow not only rice, but also other crops (grain legumes, sunflower, and vegetables) in rotation with rice in rainfed lowlands for selected districts of Maharashtra. In mid-2015, the SRT method has been taken up for expansion with a public private partnership (PPP) programme in 10 to 12 districts chosen for intensive agricultural development (IAD) in Maharashtra State. Details follow:

- An SRT frame made of angle iron and tubes is used to make 20 holes at a time at pre-determined spacing (25 cm x 25 cm) (Fig. 3.15a).
- If beds are formed earlier and there are weeds growing on beds, glyphosate herbicide (100 ml of glyphosate + 150 g of urea is dissolved in 15 liters of water) and sprayed 2–3 hrs before dibbling seeds.
- Dibble seeding: Place 3–4 granules of 15–15–15 NPK fertiliser followed by 3–4 dry rice seeds coated with *Azospirillum* and/or other effective microorganisms (EM) in each hole and close the hole with soil (Fig. 3.15b). Approximately 20 to 25 kg seed will be required for dibble-seeding one hectare. About 10% of the seeds are sown in rows located at one end of the beds for later gap filling, if necessary.
- A selective herbicide, such as Goal/Oxyfluoren (15 ml mixed in 15 liters of water in a sprayer) can be sprayed onto beds within 10–12 hrs after moistening the soil in the beds, either by rain or by irrigation. Walk backwards while spraying, taking care not to step on the sprayed surface.
- If weeds are still growing even after two selective herbicide applications, apply early post-emergence herbicides – Almix (metsulfuron methyl 10% + chlorimuron ethyl 10%) for broad leaf weeds and Clincher (cyhalofop butyl) for grassy weeds (but safe for rice), at 10–15 DAS [18].
- Gap filling: The first gap filling is done immediately after germination (5–6 DAS) by placing 3–4 sprouted seeds into each hole (with no rice plant) and covered with soil. The 2nd gap filling is done at 15–20 DAS (seedlings are at the 4–5 leaf stage). Here, rice seedlings grown at the ends of the beds are carefully uprooted and planted in missing hills (Fig. 3.15c). By gap filling two times an optimum rice plant population is maintained.

(a) (b) (c)

FIG. 3.15. Direct manual dibbling of dry rice seeds on raised beds (SRT Method): (a) Making holes with the SRT Frame on the moist bed; (b) Placing 3–4 granules of 15:15:15 NPK fertiliser followed by 3–4 rice seeds per hole and then closing the hole; and (c) 2nd Gap filling by planting rice seedlings into hills of missing plants [17].

3.7. WATER MANAGEMENT

This section describes irrigation management systems for various types of rice ecosystems.

3.7.1. Irrigated rice – water management

Flood irrigation is the most commonly used system for irrigating rice in Asia and elsewhere. When a rice field is flooded, three types of water saturation occur in rice soils: (a) endo saturation, in which the entire soil profile is saturated with water; (b) epi saturation, in which the upper soil layers are saturated, but the underlying subsoil layers remain unsaturated; and (c) anthric saturation, which is a variant of epi saturation with controlled flooding and a puddled surface soil [2]. Flooding of rice fields has beneficial effects on soil acidity (pH), soil organic matter buildup (due to anaerobic conditions), weed suppression, availability of P, Fe and Zn, and biological N_2 fixation that supplies additional N to rice crops [18]. Flooding the rice fields also helps to recharge the groundwater in the vicinity. Although, at the individual field level, irrigated rice crops receive 2 to 3 times more water per hectare than other irrigated crops, an unknown portion of the water lost from upper rice fields is reused by rice crops in fields downstream [2]. However, due to growing water scarcity and due to competition for water from sectors other than agriculture, either reducing water use or increasing water use efficiency is critical in the future for irrigated agriculture.

Why and how to save water in irrigated rice: The transplanted, flooded rice growing system is a major consumer of freshwater resources. For one irrigated rice crop, 38% of the water is used for land preparation, 31% is lost by a combination of evaporation plus transpiration (evapotranspiration) and 31% seeps into, or percolates through the soil (the percentage of seepage will be higher for sandy soils). In all of Asia irrigated agriculture accounts for 90% of the total diverted freshwater and about half of this agricultural water is used to irrigate rice.

Water quality, however, is declining and at the same time its availability is being reduced. These two factors, together with increasing competition for irrigation water and the rising costs of freshwater for irrigation use, are now threatening the sustainability of irrigated rice cropping systems across Asia. It is estimated that by 2025, about 2 mha of irrigated dry season rice and 13 mha of irrigated wet season rice in Asia will experience a ‘physical water scarcity’. Further to this, most of the 22 mha of irrigated dry season rice in south and Southeast Asia will suffer an ‘economic water scarcity’ [19].

Asia, then, needs to adopt water saving irrigation methods in order to prevent a severe water shortage. To accomplish such ‘water savings’ in irrigated rice cropping, the selection of short growth duration rice varieties, the maintaining of a shallow water depth (2–5 cm), the use of dry tillage for land preparation, and utilisation of proper land levelling methods will all be helpful.

Three methods of irrigation that are highly efficient in water use are: (a) alternate wetting and drying (AWD) irrigation on flat land; (b) furrow irrigation for rice and other crops which are planted on raised beds or on ridges; and (c) drip irrigation (specifically for aerobic rice fields).

3.7.1.1. Alternate wetting and drying (AWD) irrigation

AWD is currently the most successful method for reducing both of water use and greenhouse gas (CH_4) emission in irrigated rice production systems. That said, NO_2 emissions may increase for aerobic rice field soils. The AWD irrigation method thus has the potential to reduce the GHG emission impact of irrigated rice agriculture by one third, relative to the continuously flooded rice system [20, 5]. The following steps describe AWD irrigation:

- Level the field well after ploughing and puddling. This will allow a uniform water distribution with a minimal amount of irrigation water.
- Maintain a thin film of water for upto 10 days after transplanting (DAT) or 21 days after direct seeding (DAS).
- Thereafter, irrigate the field to a water level of 2 to 5 cm, allowing the water to disappear over time. Then irrigate again when small cracks begin to develop in the soil (Fig. 3.16).
- Maintain a water level of 2 cm while weeding with a rotating hoe/mechanical weeder.
- Repeat the process of AWD up to the stage of maximum tillering (about 40–45 DAT or 50–55 DAS) for short growth duration rice varieties and (55–60 DAT or 65–70 DAS) for medium to long growth duration rice varieties.
- Then maintain continuous flooding with a 2 to 5 cm level of water from the panicle initiation stage to crop maturity.
- Finally, allow the field to dry for 15 days prior to harvesting – this will hasten grain maturity and improve the condition of the soil for the crop harvesting operations, specifically harvesting by machines.

FIG. 3.16. An example of alternate wetting and drying (AWD) irrigation (a water level of 2 to 5 cm was added when the water from the previous irrigation has disappeared) are maintained up to the stage of maximum tillering (Photo by V. Balasubramanian).

3.7.1.2. Furrow irrigation for rice and other crops which are planted on raised beds

Irrigation water is released into gently sloping furrows between the raised beds and allowed to move laterally out into the beds so the crops planted on the raised beds will receive adequate water (Fig. 3.17). During heavy rains, the same furrows will serve to quickly drain the excess water away from the raised bed. Thus, furrows facilitate both irrigation and drainage in raised bed farming. Furrows also help in the percolation of water into the ground, thereby helping to build up and maintain an optimal groundwater table [17].

FIG. 3.17. Furrow irrigation: furrows serve to irrigate crops planted on raised beds, and also can be used to drain excess water away during heavy rains. Standing water can also penetrate the ground, thereby maintaining an optimal groundwater table [17].

3.7.1.3. Drip irrigation

Drip irrigation, also known as 'trickle' irrigation, encompasses all approaches that involve applying water directly to the soil along a row, around crop roots. Under this system, water moves through a network of narrow plastic pipes under low pressure and is delivered to the root zone of the rice crop, drop by drop through drippers (Fig. 3.18). When water availability is limited, the drip irrigation system can be used to wet the soil in seeded rows to facilitate a uniform germination and obtain better crop emergence and early crop growth in direct seeded crops. It is also well suited for widely spaced horticulture and plantation crops, and for vegetable crops. Drip irrigation thus helps in the optimisation of water resources in water scarce areas. The drip irrigation system has the potential to reduce irrigation water use by up to 70%, while increasing crop yields by 20 to 90%. The advantages include a 50–60% saving of water compared to flow or flood irrigation, an efficient use of fertilisers when fertigation is used, e.g. a precise supply of water soluble fertiliser is added into the irrigation water. This allows fertilisation directly to the plant's root system, and also allows changing fertiliser rates as the crop's requirement changes at the different growth stages. Less labour is needed and energy costs for irrigation are reduced. In addition, drip irrigation reduces the salinity hazard to crops planted in saline soils by diluting the salt content in the crop root zone, and/or moving the salts below the root zone. Drip irrigation also reduces weed growth as the water is supplied only to crops' root system; and fertigation facilitates the application of fertilisers to nourish plants. The limitations of drip irrigation system are its high initial cost which small and marginal farmers cannot afford without receiving a government subsidy or bank loan. A technical knowledge and skill are needed to install and maintain the drip system which many farmers currently lack. Blocking of drippers by evaporated salt and algal/fungal growth occurs commonly, especially when poor quality water high in dissolved salts is used. Other problems include poor quality irrigation pipe, drippers, connectors, etc. and there is often limited or poor technical support and after sales service provided by dealers. Finally, the improper disposal of damaged plastic pipes/tubing (used in mains, submains, and laterals) creates litter and pollution, especially if burned at low temperature.

FIG. 3.18. Drip irrigation system for rice.

For rice crops which are grown in un flooded soil, in a manner similar to upland crops (maize, wheat, soybean, etc.), drip irrigation can be very effective in terms of efficient water use and application of fertilisers as per crop demand, through irrigation water. Drip irrigation of direct seeded rice crops uses only about a third (8.04 million litres ha^{-1}) of the water used in flood irrigated fields (25.69 million litres ha^{-1}), and the power consumption for pumping water can be reduced by half (from 1154 units for flood irrigation to 558 units for drip irrigation, per hectare).

As is the case for alternative wetting and drying (AWD), the drip irrigation system has the potential to reduce CH_4 emission by up to 50%, though N_2O emissions increase in aerobic rice fields. The high initial cost of installing a drip system, the increased N_2O, a deep percolation of water in unpuddled soil, and a high infestation of weeds due to simultaneous germination and growth of weeds along with germinating rice seeds, can be important constraints in direct seeded, drip irrigated crops. Moreover, rice crops grown in aerobic soils often suffer from problems of decreased availability of certain nutrients (P, Fe and Zn), decreased soil pH and organic matter content, and increased incidence of soil born pests and pathogens like nematodes (*Melodoigyne graminicola*), root aphids and fungi [3, 21, 22, 23]. For these and other reasons, aerobic rice cannot be grown continuously on the same piece of land year after year without getting reductions in rice grain yield. For these reasons, drip irrigation of aerobic rice is very limited at present.

3.7.2. Managing water in rainfed lowland rice

The risks of both flood and drought are the most critical constraints to successful rain-fed lowland rice farming. For all rice varieties the water requirement is the highest during the reproductive phase (from panicle initiation to heading), and during this period rice fields have 2 to 5 cm of standing water. Any moisture deficit (due to drought) during this critical period will seriously affect spikelet formation and grain filling, resulting in a drastic reduction in yield, or even a complete crop failure.

3.7.2.1. How to manage water in flood prone lowlands:

- Selection of rice varieties: Farmers plant flood tolerant rice varieties (e.g. Swarna Sub1, Samba Mahsuri-Sub1, CR1009-Sub1, IR64-Sub1, Ciherang-Sub1, TDK-Sub1) to increase and stabilise rice yields in flood prone lowlands. Varieties with the Sub1 locus incorporated have shown a yield advantage of 1–3 t ha^{-1} following flooding for 10–14 days.
- Flood water management: Farmers use reservoirs and/or large community ponds to regulate flash floods, thereby minimizing crop damage.
- Drainage: There is adequate drainage provided to reduce iron toxicity, thereby stabilising rice production in poorly drained fields.
- Planting rice on ridges or raised beds: Plant rice seeds or seedlings on small ridges or raised beds separated by furrows. Then, use the furrows to irrigate when the soil is dry, or to drain the excess water during heavy rains in order to reduce the adverse effects of excess iron and aluminium in poorly drained lowlands. This will also help to reduce excess salt in saline soils.

3.7.2.2. How to manage rainfall and available water in drought prone lowlands:

- Selection of rice varieties: To date 17 high yielding, drought tolerant rice varieties have been developed and released to farmers in different countries of Asia and Africa. Farmers plant the best suited, drought tolerant (aerobic) rice varieties (Apo in People's Republic of China, Sahbhagi Dhan India in India, Sahod Ulan in the Philippines, Sookha Dhan in Nepal, TDK9, TDK11, TDK12, Phon ngam 1 and 3 in Laos) to increase or stabilise rice yields in drought prone lowlands.
- Rainwater harvesting: Farm ponds, small community reservoirs or earth dams across water courses are built. These can help collect and store rainwater from peak floods, and are especially useful in both drought and flood prone rainfed lowlands. Water storage in farm ponds and nearby water bodies will also help to recharge groundwater, and revive small streams on nearby land areas, thereby increasing water availability in rural (farming) areas.

- Wetting the soil in seed rows: Use a drip system or other appropriate means to wet the soil in seed rows to facilitate uniform germination, obtain better crop emergence and earlier crop growth in direct seeded rice crops when water is available from farm ponds.
- Lifesaving irrigation: Use the water from farm ponds or community lakes (Fig. 3.19) to provide one or more lifesaving irrigations to the rice crop during periods of drought at critical growth stages (see above). This will increase or stabilise rice grain yields and reduce the risks associated with drought. Once supplementary irrigation becomes available, farmers will tend to apply additional inputs, such as fertilisers, in order to enhance rice productivity on rainfed lowlands fields.
- Improving soil organic matter content and soil fertility: Fertile soils with higher soil organic matter content will enhance the absorption and retention of rainwater in soils. This, in turn, will ensure a better and more uniform seed germination and enable the rice plants to tolerate short dry spells.
- Surface mulching: Use any type of mulching on the soil surface that will help conserve soil moisture for un puddled direct seeded rice fields, but not in flooded (and often puddled) lowlands.
- Diversification: Pond water can also be used for cultivating additional crops in the dry season, growing fish, and raising ducks and chickens (Fig. 3.19).

FIG. 3.19. Farm ponds can provide water for life saving irrigation of crops during periods of drought (Photo by V. Balasubramanian).

3.8. TACKLING SOIL SALINITY AND ALKALINITY IN RAINFED AND IRRIGATED LOW-LANDS

Salinity and alkalinity management is critical for improving the productivity of irrigated rice in semiarid areas, and also in coastal wetlands. Among the management practices that minimise salinity problems are selection of salt tolerant rice varieties and crop rotations. There is also land levelling, followed by salt leaching with irrigation water – this will have long term effects. In contrast, tillage, fallowing and mulching, landform (ridges and furrows or raised beds and furrows) and planting method, and the application of manures, fertilisers, and amendments (e.g. gypsum), while useful, will have only a short-term effect [24]. Any tillage that improves internal drainage and mulching that reduces evaporation will help reduce salt accumulation on soil surface. In addition, effective management of waste water and saline water for irrigation is also important. Proper fertilisation with mineral nutrients will not affect salinity.

3.9. SOIL FERTILITY MANAGEMENT: SITE SPECIFIC, INTEGRATED NUTRIENT MANAGEMENT

Optimizing mineral nutrients is the key to increasing food production to feed the predicted expanding human population. The mineral elements, taken up from soils and from added organic materials and fertilisers, are divided into two groups: macro nutrients (required in large quantity) – N, P, K, Ca, Mg, S, and Si; and micro nutrients (required in small amounts, excess will often be toxic) – Fe, Mn, B, Mo, Cu, Zn and Cl. The amount of various nutrients absorbed by crop plants is highly variable depending on the type of plants and availability of nutrients in soils [25].

Naturally occurring soil nutrients, together with added organic manures, contribute to slightly more than half of the global food production. Mineral fertiliser nutrients added by farmers are responsible for the rest of the global food production. Both insufficient and excessive nutrient applications can have serious impacts on resource quality and resource use efficiency (soil, water and air), as well as crop (grain) production efficiency, food quality, greenhouse gas emission (and thus climate change), biodiversity and ecosystem services, and environmental quality. The greatest challenge to food crop farming in the 21st century is to increase food production while lowering its environmental footprints (low nutrients losses to air and water bodies. According to Sutton et al. 2013 [26], major impacts of improper nutrient use on the earth's environment are:

- Soil quality: Over fertilisation with selective nutrients (N, NP, or NPK only) and deposition of too much atmospheric 'reactive' N can acidify forest and arable lands and degrade soils, due to nutrient excesses and nutrient imbalances, and also by a reduced microbial diversity. In contrast, application of too little or no nutrients leads to soil nutrient depletion and soil degradation. Intensive cropping, with removal of all crop residues, can lead to a significant reduction of soil organic matter.

- Water quality: Movement of excess N and P to our water resources leads to nitrate pollution of drinking water, algal blooms, eutrophication, hypoxia, fish killing and coastal and freshwater 'dead' zones.

- Air quality: Air pollutants that impact human health includes particulate matter ($PM_{2.5}$) formed from NOx, NH_3 emissions, and increasing concentrations of N_2O and ozone (O_3).

- GHG emissions: Emissions of CH_4 from flooded rice systems and N_2O from aerobic soils will exacerbate global warming and increase the pace of climate change. Interactions of N_2O with atmospheric reactive N forms, particulate matter (PM) and tropospheric O_3 will lead to an increasing depletion of stratospheric O_3 and an increased irradiance of UV wavelengths, thereby increasing the incidence of human skin cancers.

- Ecosystem services and biodiversity: Loss of natural habitats due to conversion of forest land to intensive agriculture (with its excessive use of fertilisers), loss of wild species due to cultivation of only a few high yielding crop varieties, and destruction of pollution sensitive species by atmospheric reactive N deposition and acid rain are serious threats to biodiversity and the health and services provided to humans by natural ecosystems.

Overall, a proper nutrient management onfarm is critical for high crop productivity, maintenance of soil quality, enhancement of resource use efficiency, and preservation of biodiversity, ecosystem services and environmental quality. The unique properties of flooded soils make rice different from any other crop. Because of prolonged flooding in rice fields, farmers are able to conserve soil organic matter and also receive free input of useful N from biological sources [18] at a rate that can maintain a certain base level of rice yield (2–3 t ha^{-1}). For higher rice yields in intensive farming systems, however, farmers have to apply more nutrients.

Integrated nutrient management (INM) promotes the application of both organic nutrient sources and chemical fertilisers in order to enhance crop productivity while maintaining soil fertility and soil health. As nutrient needs of rice plants vary with variety and stage of growth, farmers tailor nutrient management to the specific conditions of their fields if they are to increase crop yields.

Nutrient needs of rice vary from one field to another. However, it is not practical to recommend to farmers specific fertiliser doses for individual fields. Farmers thus use either blanket fertiliser doses or implement site specific nutrient management (SSNM) in order to ensure all required nutrients (e.g. N, P, K, S and Zn) are available to rice plants in a timely and balanced manner. If that can be accomplished, rice farmers will be able to grow healthy, robust crops and consistently obtain high yields.

3.9.1. Proposed general fertiliser doses

Below section describes the generally recommended fertiliser doses for rice crops. These suggestions or proposals are not from IAEA but rather based on the field studies conducted in different countries in Asia. These include:

- In so far as possible, incorporate residues from the previous crop into the soil during land preparation.
- Apply and incorporate into the soil, manure, compost or green manure – up to 5 t ha^{-1} – whenever possible. Application of organic matter (manure or compost) is especially important for sandy soils, i.e. in the northeast of Thailand and also in other countries in the south and southeast parts of Asia.
- Use inorganic mineral fertilisers to further increase crop yields.
- In addition to organic manure and compost, to be applied at rates up to 5 t ha^{-1}, also apply N–P–K at the following recommended rates, i.e. at 60 to 90–15–25 kg ha^{-1} for wet season irrigated or rainfed lowland rice crops, and at 100 to 150–26–50 kg ha^{-1} for dry season irrigated rice crops. Specifically, apply one-third of the N, all of the P, and one half of the K prior to planting. Then apply a 2nd application of N at the stage of maximum

tillering, and a 3rd application of N (and the 2nd application of K) at either the panicle initiation or booting stage.

- When N is applied in the form of compressed urea tablets, a single 'deep placement' of each urea tablet at 15 days after transplanting (DAT) or 21 days after seeding (DAS) appears to be optimum, because crop demand for N is low when the rice crop is at the seedling stage. A single (one gram) urea tablet is thus manually placed deep in the soil at the center of each of four hills, with the help of a locally made deep placement tool for transplanted rice. In rows of direct seeded rice, one urea tablet is placed deep in the soil every 20 cm in distance for each alternate row [27, 28].
- These rates of fertilisation double the crop yield from a base level of 2.0 to 2.5 t ha^{-1} expected for unfertilised fields, to a crop yield of 5.0 to 8.0 t ha^{-1} after application of the inorganic mineral fertilisers.
- The inorganic fertiliser rates above are blanket fertiliser doses for rice crops based on data collected from various field trials in Asia. The rates are lowered somewhat for traditional rice varieties due to their marginal response to applied fertilisers. Lower inorganic fertiliser rates may also be needed for drought or flood prone areas.

3.9.2. Site specific integrated nutrient management

Site specific nutrient management (SSNM) helps farmers to apply required nutrients to rice crops based on the actual crop needs and the variability of the current soil nutrient supply (Fig. 3.20) [29, 30, 31]. Both organic and inorganic fertiliser sources of nutrients are used in SSNM to meet crop needs. Additionally, though, farmers also use good quality seed, optimise plant density, incorporate integrated pest management, and maintain good water management to maximise the benefits from using SSNM. The steps used to accomplish SSNM are:

- As mentioned above in several places, the farmer applies all organic materials (straw, compost, manure, ash, green manure, etc.) by incorporating them into the soil during land preparation.
- Supplement the organic materials with applications of inorganic mineral fertilisers in order to meet additional crop needs:
- For example, use of a leaf color chart (Fig. 3.21) will assist the farmer in the application of proper amounts of additional N mineral fertiliser to rice crops – i.e. use of this simple technique will identify differing crop needs in different fields [32, 33].
- Apply P and K fertilisers as per local SSNM practices.
- Apply sulfur, zinc and other micronutrients only to soils that are deficient in these elements, again based on local SSNM practices. Farmers need to note that zinc (as zinc sulphate) is often applied onto the surface of moist soil about two weeks after seedlings are transplanted into the main field.
- Finally, the farmer selects the most cost effective sources of mineral fertilisers.

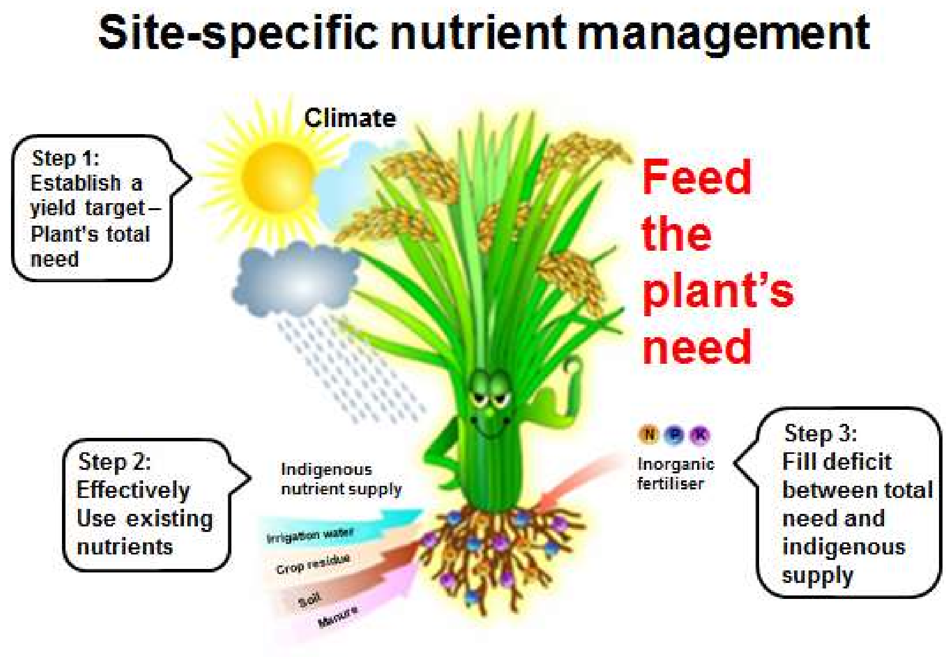


FIG. 3.20. Site specific nutrient management (SSNM) using organic and inorganic fertilisers as nutrient sources [29].

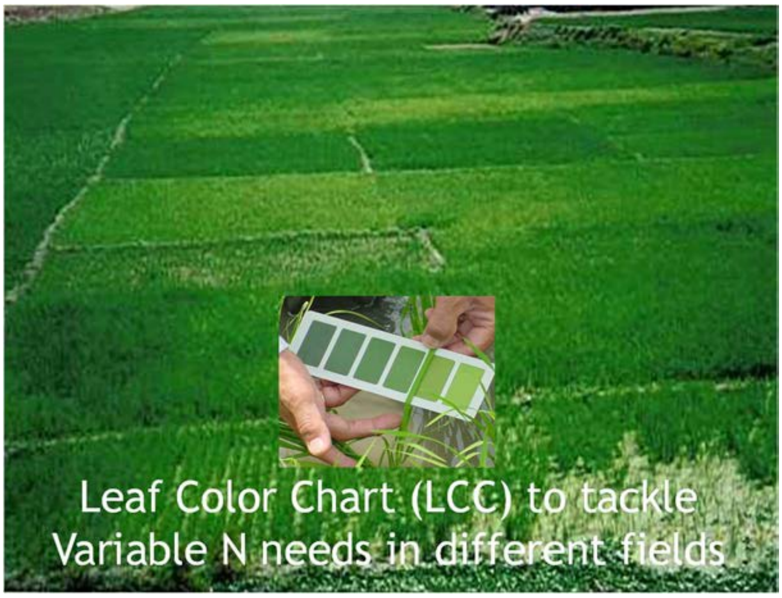


FIG. 3.21. Leaf colour chart (LCC) – a simple tool for judging how much mineral N fertiliser are applied, based on expected crop demand and variability in soils [32].

3.9.3. Overcoming iron toxicity

Excess soluble iron is especially toxic to rice crops (Fig. 3.22) growing on soils that are poorly drained, and also in fields which remain flooded all the time. To reduce iron toxicity, avoid planting susceptible rice varieties like IR64. Also, dig furrows at regular intervals and, whenever necessary, drain the excess water into the furrows. Planting of rice on the upper sides of ridges, or on raised beds, together with furrow irrigation and the application of balanced (N, P, K and Zn) fertilisers will reduce iron toxicity appreciably. Applying extra K fertiliser to rice crops which are severely affected by iron toxicity can also be helpful [34].

FIG. 22. Iron toxicity causes stunted growth and leaf bronzing – a serious problem in poorly drained and continuously flooded rice fields (Photos by V. Balasubramanian).

3.10. INTEGRATED WEED MANAGEMENT

Weeds, if left uncontrolled, are one of the most serious biological constraints to lowland rice production [35]. Weeds compete with rice plants for space, light, water and nutrients, thereby inhibiting crop growth and reducing rice yields drastically [36]. Weeds can also reduce grain quality (via an admixture of weed seeds in the harvested grain); serve as alternate hosts for insect pests and diseases, and provide a safe habitat for rats which often attack rice crops; all of which increase rice production costs. Finally, weeds, especially late season weeds such as red rice, can interfere with rice grain harvesting. Rice yield loss due to weeds is believed to be 10–25% in Asia and 25–40% in sub Saharan Africa, with total crop losses occurring in extreme cases [37]. Although weeds do compete with rice crops, some weeds can be useful to subsistence farmers as food and herbal medicine for humans, thatching material for housing, fodder for animals or as substrate for composting [38, 39].

Lowland rice is frequently affected by aquatic type weeds: grasses, sedges, broadleaf weeds, and some perennial species (Fig. 3.23). Grass weeds are a problem early in the growing season and broad leaf weeds and sedges compete with rice crops during the reproductive and grain ripening stages. Perennial aquatic weeds that germinate and thrive in flooded fields are the most difficult to control. Rice crops originating from transplanted seedlings tend to have fewer weeds, relative to direct seeded crops. Weed infestation is serious wherever water control is poor, as in most rainfed, poorly managed irrigated areas. Improper land preparation and poor land levelling lead to a non-uniform cover of water (and more weeds) in irrigated rice fields [40, 41].

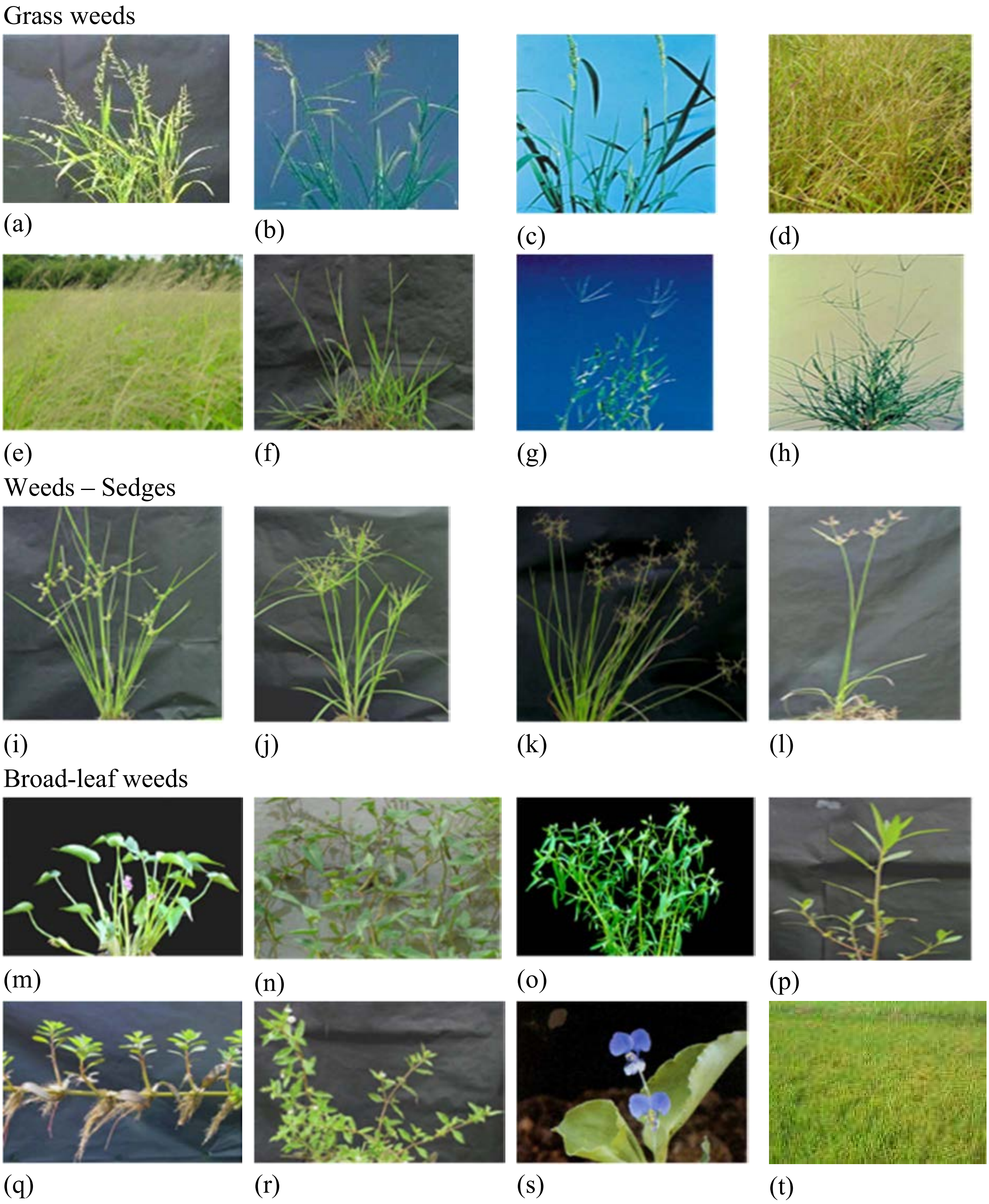


FIG. 3.23. Major weeds of lowland rice in Asia. (a) Echinochloa colona; (b) E. crus-galli; (c) E. glabresecens; (d) Ischaemum rogusum; (e) Leptochloa chinensis; (f) Paspalum distichum; (g) Digitaria setigera (h) Eleusine indica; (i) Cyperus difformis; (j) Cyperus iria; (k) Fimbristylis miliacea; (l) Cyperus rotundus; (m) Monochoria vaginalis; (n) Ipomoea aquatic; (o) Sphenoclea zeylanica; (p) Ludwigia octovalvis; (q) Ludwigia adscendens; (r) Eclipta prostrata; (s) Commelina bengalensis; and (t) Rice field with sedges (Source: www.knowledgebank.irri.org/).

A timely intervention is critical for effective weed control in rice, as in most other crops. Integrated weed management will use a combination of cultural, manual, mechanical and/or chemical weed control methods.

3.10.1. Cultural weed control methods

Cultural weed control is generally ecologically sound because it avoids the use of chemical herbicides; it is also easy to use and often cost effective. It adopts the principle of 'prevention is better than cure' as discussed below.

- Well prepared and level crop fields can reduce weeds by up to 40%.
- Selection of weed competitive rice varieties, ones with early seedling vigor (rapid early growth) and a high frequency of tillering, will also help to suppress weeds [36, 41].
- Use of good quality seed; keeping the rice nursery, field bunds and irrigation channels free of weeds; and the rotation of crops – all as weed control methods, will help to break weed cycles and thus minimise weed infestation. Similarly, transplanting healthy, vigorous seedlings; maintaining a uniformly distributed rice plant population; and applying N fertiliser just after weeding will minimise competition from weeds.
- Water is the best natural *'herbicide'* to control weeds. Maintaining a 2 to 5 cm water level in the fields can minimise weed emergence, thereby reducing competition from weeds (this is especially useful for control of grassy weeds and also some sedges).
- Reducing the weed 'seed bank' in the soil by killing weeds in fallow fields before they flower and set seed is especially useful (remember the phrase – 'one year seeds, seven years weeds').

3.10.2. Manual (hand) weeding

Many resource poor farmers remove weeds by hand (Fig. 3.24). Although it provides employment for landless rural people, the drudgery and a growing scarcity of labour are making it less likely that manual weeding will be performed, in the future, in a timely fashion. Even so, a brief discussion of how best to hand weed is given below:

- Start hand weeding when weeds are large enough to grasp, i.e. about 20 to 25 days after transplanting (DAT) rice seedlings, or 30–35 days after direct seeding (DAS).
- Repeat the weeding once or twice more at 30–35 and 40–45 DAT or 40–45 and 50–55 DAS.
- Never allow weeds to flower and set seeds in the rice crop's main field.
- Weed the rice field before applying N and other fertilisers so as to minimise nutrient uptake by weeds.

FIG. 3.24. Manual weeding – very effective, but tedious and labour intensive.

3.10.3. Mechanical weeding

Mechanical weeding involves inter row cultivation to uproot and bury young weeds. It is a non-chemical, ecologically sound method and is more efficient and less labour intensive than hand weeding. The soil stirring that occurs in mechanical weeding is considered by some to increase all of root and shoot growth, tillering, and thus grain yield of the rice plants. However, mechanical weeding can be used only for crops planted in rows.

- With 2 to 3 cm of water on the rice field, begin by using a rotating hoe (rotary or cono-weeder) (Fig. 3.25) at 10–12 DAT or 20–22 DAS when weeds that have emerged are quite young (prior to the 4 leaf stage).
- Repeat the mechanical hoeing one or two more times, i.e. at 20–22 and 30–32 DAT, or 30–32 and 40–42 DAS.
- Additionally remove the weeds missed by the hoe, or within the row or near the rice plants by hand.
- Generally, mechanical hoeing is done up one row and back down another row, unless the field is planted in a square pattern of rows. If that's the case, then the rotating hoe can also be used in the perpendicular direction.

(a) (b)

FIG. 3.25. Different types of rotating hoe weeders used in rice crops planted in rows: (a) Rotating hoe (rotary, cono and single drum) weeders; (b) Mechanical weeding accomplished by a cono weeder (Photos by V. Balasubramanian).

3.10.4. Chemical weed control

Herbicides can be used before planting or just after direct seeding (e.g. pre-emergence herbicides), or after emergence of both weeds and rice seedlings (Fig. 3.26) in order to kill specific weed species, or to inhibit their growth. Herbicide application requires less labour (0.5 person day per hectare for one application) and is cost efficient. If chosen properly and applied correctly, herbicides can give an effective control of weeds. However, application of the same herbicide, season after season can sometimes lead to the development of herbicide resistance. Use the following steps to apply herbicides correctly:

- Select an appropriate herbicide for the weeds to be controlled, and the stage of the rice crop. Be certain to use the recommended rate of application.
- Some herbicides are designed to control the weeds before they emerge (i.e. pre-emergence), while others are only effective after the weeds have emerged (post-emergence).
- Always read and follow the instructions on the product label.
- Ensure field conditions are suitable for herbicide application (e.g. some herbicides only work optimally when the soil is moist and the humidity is high).
- Mix the recommended amount of herbicide with required amount of clean water in a suitable sprayer, one which has an appropriate spray nozzle.
- Uniformly apply the herbicide + water mix across the field: maintaining a steady pressure by pumping and a steady walking speed. This will ensure a uniform spray application action.
- Spray the herbick;ide product from a height of around 50 cm above the target plants.
- Spray ideally only on calm days, or if there is a minor wind, spray perpendicular to the wind, so that herbicide spray is blown away from the person applying the spray.
- Rotate the herbicide 'types', insofar as possible, in subsequent years to help prevent the development of herbicide resistant weeds.

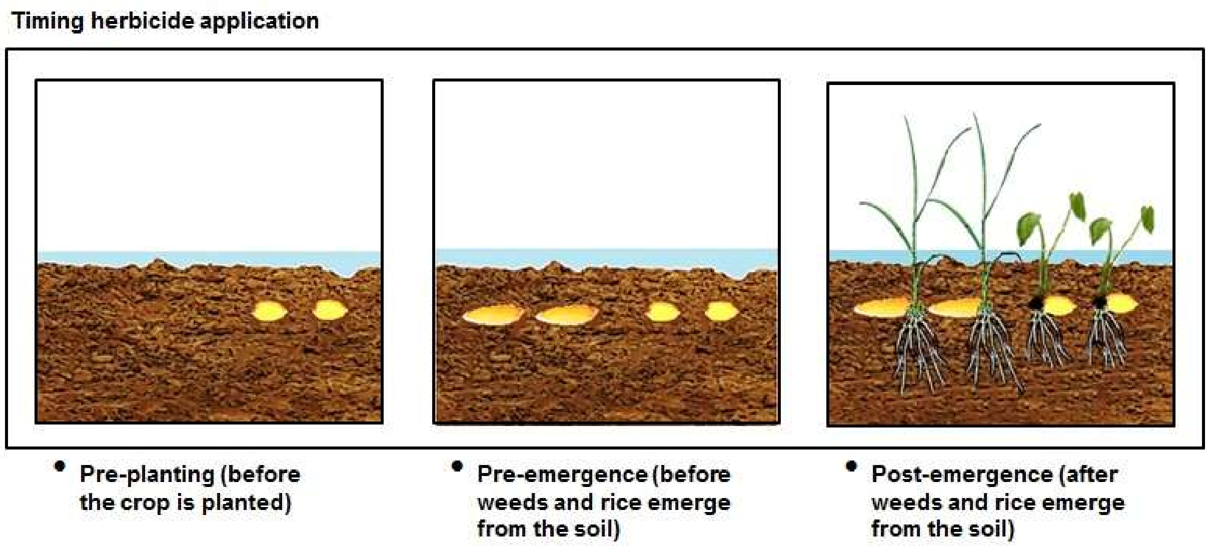


FIG. 3.26. Timing herbicide applications in rice: Pre-planting, pre-emergence (for pre-emergence herbicide use), and post-emergence (for post-emergence herbicide use).

3.11. INTEGRATED PEST MANAGEMENT (IPM)

This section describes the different insect pests and diseases that attack rice crop at different growth stages as well as their control using integrated approach.

3.11.1. Insect pests, diseases and non-insect pests of lowland rice

- Important insect pests which attack seedlings in a rice nursery are army worms, rice thrips, green leaf hopper (GLH), and case worm. Insect pests that attack older rice plants in the main crop field are stem borers, leaf folder, brown plant hopper (BPH), white bagged plant hopper (WBPH), GLH, gall midge, whorl maggot, rice thrips and black bug (Fig. 3.27).
- Bacterial diseases include bacterial blight (BB), bacterial leaf streak, and brown spot. Fungal diseases include blast, sheath blight, sheath rot, false smut, and a fungal complex causing grain discoloration. Viral diseases are also important in many Asian countries, including Laos, e.g. tungro, ragged stunt, grassy stunt and yellow dwarf viruses.
- Non-insect pests that occur in Asia include nematodes, the golden apple snail, crabs, crickets, rats, birds, etc.
- Early applications of broad spectrum insecticides on rice crops to control leaf eaters often results in a subsequent resurgence of plant hoppers and leaf hoppers. In addition to their direct damage to crops, the plant hoppers and leaf hoppers can also act as vectors of some rice viruses, such as tungro, ragged stunt, grassy stunt and yellow dwarf. Two stem and two root knot nematode species attack rice plants in both deepwater and rainfed lowland areas. Rats also damage rice crops in the field as well as rice grains in storage. A number of bird species are also destructive, eating the mature grains in the field. In southeast Asia intensive cropping systems with grain yields of 5 t ha^{-1} or more, can suffer yield losses as high as 37% due to damage from a combination of insect pests and diseases.

FIG. 3.27. Examples of some of the different insect pests that attack rice in Asia (Picture credit: G. Ravi, Tamil Nadu Agricultural University, India).

3.11.2. Chemical pest control – pesticides, herbicides, fungicides

Pesticides are poisons that kill insects, pathogens and weeds, bu some of them can also harm wildlife and humans, as well as pollute the enviornment. Globally, in 2012, farmers applied 3.5 mt (active ingredients) of pesticides to control pests on food crops. Pesticide use is currently increasing at a cumulative annual growth rate 7%. Thus, pesticides are a huge global business, worth about US $45 billion per annum. Major problems associated with the widespread use of chemical pesticides are: an increasing persistence of pesticide residues and/or their by-products in the environment; a non-specific mode of pesticide action; difficulty in applying the pesticide only to the target organisms; cumulative and sub lethal to lethal effects on humans and other animal species; a high incidence of pesticide misuse; the resurgence of secondary pests following preventive application of pesticides at early crop growth stages; and the development of pesticide resistance.

Excessuse use of pesticide can seriously affect the farmers' health and productivity, and may also negatively influence native wildlife. Consumers can also be affected by pesticide residues in the food. Pesticide residues and off target pesticide drifts pollute both soil and water resources, thus degrading the environment. Rachel Carson's book *Silent Spring* published in 1962 [42], as well as other reports discuss the adverse impacts of chemical pesticides on human lives, biodiversity, natural resources and the broader environment. Each kg of pesticides used in agriculture is estimated to impose an external economic cost US $4 to US $19 on the environment via remediation of pesticide contaminated sites, wildlife (including loss of pollinators), and human health (removing pesticides from potable water, treating pesticide related ailments) [43].

3.11.3. Integrated pest management (IPM)

IPM is defined as the integrated use of various non-chemical pest control tactics prior to resorting to the use of chemicals for pest control. The three cardinal principles of IPM are: (i) growing a healthy crop by adopting resistant varieties and best crop management practices; (ii) maintaining pest predator balance by establishing and maintaining a healthy agro- ecosystem; and (iii) the strategic use of external pest control inputs that are known to have a minimal impact on the agroecosystem. IPM is thus a knowledge intensive approach, one which requires systematic learning through continuous observation and practice (e.g. via Farmer Field Schools), and depends upon social capital for successful implementation. The sustained hard work required to implement IPM will pay off through increased crop yields, reduced cost on purchase and application of pesticides, and improved human and wildlife health, as well as an improved environmental quality. An analysis of 85 IPM projects from 24 countries of Asia and Africa which have been implemented over the past 20 years (1994–2014), indicate that crop yields have been increased by an average of 40.9% (Standard Deviation was 72.3) while pesticide use decreased by 30.7% (Standard Deviation was ±34.9), all relative to baseline yields. Unfortunately, policy and institutional support for IPM remains lukewarm [43].

IPM tactics: Farmers currently can use any of the six IPM tactics listed below for managing pests in their rice crops: (i) agronomic/cultural practices – cultural control; (ii) mechanical methods; (iii) biological control; (iv) genetic: host plant resistance; (v) use of naturally occurring plant products – i.e. effective and relatively safe botanicals and microbial bio pesticides; and (vi) judicious chemical control with 'soft' pesticides, which are used on a need only basis.

Agronomic/Cultural pest control methods which have been shown to be effective:

- Selection of a well drained site for the rice seedling nursery, application of neem seed cake to the nursery bed where susceptible pests are present, use of pest resistant/tolerant rice varieties and use of clean/healthy seed. Also, seed treatment with bio contol agents such as *Trichoderma viride* at one teaspoonful (4–5 g) per kg of seed or *Pseudomonas florescens* at 2 teaspoonsful (10 g) per kg of seed will protect the seedlings from seed borne pathogens that cause root rot, seedling wilt, and seedling blast. As biocontrol agents are compatible with bofertilisers, farmers can treat the seeds simultaneously with biocontrol agents, and with biofertilisers like *Azospirillum* and Phosphobacteria (a culture of bacteria that solubilise soil P).
- In the main rice field, farmers can use crop rotation, mixed cropping or intercropping, barrier or trap crops which are effective in reducing pest populations, synchronised planting and harvesting, enhanced field sanitation (keeping fields, bunds, irrigation channels free of weeds), management of field water levels and fertiliser applications, etc. All of the above approaches can be used in ways which are designed to minimise pest and disease incidence. Some examples of cultural control methods are:
- Adjust time of planting to minimise attack by stem borer and rice root weevil
- Burn, or bury into the soil, rice plant stubbles that can harbor stem borer eggs
- Flood the rice field to prevent the attack on seedlings by root aphids and mole crickets
- Drain the rice field periodically to control caseworm damage and allow the farmer to collect golden apple snails that accumulate in drainage channels
- Transplant rice seedlings at an older age, if feasible, to prevent whorl maggot attack
- Apply N fertiliser in two or three split applications so as to prevent build-up of brown plant hoppers and Asian rice gall midge

Mechanical methods:

- Collecting and destroying egg masses of stem borers and hispa, caterpillars, crabs and snails; exclude pests by screens or barriers (e.g. use of a trap barrier system for rat control can often be highly effective).
- Trapping and killing insects with suction devices, use of light or pheromone traps, nets, and other mechanical devices can all help control insect pests.
- Removing or destroying disease affected plants (or their alternate hosts) is vital in order to prevent the spread of bacterial, fungal and viral diseases.
- Drying the soil for a month or more between seasons will help reduce nematode infestation. Farmers can also use hot water (55 ºC for 12 hrs) to disinfest rice seeds in order to control white tip nematodes.

Biological pest control methods:

- Conservation of natural enemies and the planned mass release of 'safe' bio control agents are two possible methods of biological control.
- Natural biological control: Conservation of natural enemies (predators and parasitoids) to control target pests is perhaps the most cost effective and universal form of biological control that farmers can employ to control certain pests of rice. In order to conserve indigenous natural enemies and enhance natural biological control, the following strategies are recommended:
- If available, use pest resistant rice varieties that possess a high resistance to major insect pests and diseases.
- Do not apply 'preventive' or calendar based application of insecticides.
- Avoid 'early season preventive sprayings' during the first 40 days after transplanting (or 55 days after seeding).
- Only when the pest's population density reaches a damaging level, the farmer can use recommended, ideally selective, 'soft' insecticides and even these can be used as a last resort to control insect pests.
- Avoid the use of broad spectrum hazardous insecticides at all costs.
- Some habitat management options: Increasing biodiversity in rice fields can often have a positive influence on the abundance of the natural enemies of rice insect pests. Some useful options are:
- Planting grain legumes or allowing broad leaf weeds to grow on rice field bunds (Fig. 3.28a) can enhance the populations of natural enemies such as Coccinellide predators. This approach can also reduce sources of alternate grassy hosts of some diseases, such as sheath blight.
- Allowing grasses and other vegetation to grow in areas adjacent to rice fields can often provide supplementary and complementary food and offseason habitats for certain natural enemies (e.g. spiders, wasps, beetle) of rice pests.
- Use of crop mosaics (Fig. 3.28b) or rotation of rice with non-rice crops such as cowpea, mung bean, maize, bell pepper, garlic, onion, soybean, flowers, etc. These other crop species can serve as important reservoirs of natural enemies of rice insect pests during the non-rice growing season.
- Conservation of insect predatory birds (Fig. 3.28c), frogs and toads by preventing their capture from the rice environment can also enhance biological control of rice insect pests. In Bangladesh, for example, the collecting of frogs from the lowland rice environment during their breeding period is discouraged.

(a) (b) (c)

FIG. 3.28. Different ways of enhancing biodiversity in rice fields to nurture natural enemies of rice insect pests for effective biological pest control: (a) Grain legumes on field bunds; (b) Crop mosaic (biodiversity); and (c) Perches for predatory birds (Photos by V. Balasubramanian).

Host plant resistance:

- Planting rice varieties that are resistant to insect pests and diseases of rice plants, and are also tolerant to drought, flood, heat, and cold (low temperature) is a popular and highly cost-effective pest control method, one which is readily available for farmers to adopt (see section on rice varieties).

Use of botanicals and microbial bio pesticides:

- Farmers can use certain botanical origin pesticides and microbial preparations for 'ecologically sound' control of pests as shown below.
- There are several plants with insecticidal properties that can be used for ecological pest control: they include neem, papaya, '*pongam*' (*Pongamia pinnata*), calotropis, custard apple, euphorbia, lantana, lemon grass prosophis, etc. Extracts or powders of plant parts, including seeds, oil extracted from seeds or oil seed cake can be used to prepare these botanical pesticides.
- Other bio pesticides include microbial pathogens like *Bacillus thuringiensis* (Bt.) preparations which are used for control of stem borers and leaf folder, and *Pseudomonas florescens* preparations (powder) used for seed treatment or as sprays on rice crops to control rice root and white tip nematodes.

Chemical control (selective use of 'soft' pesticides):

- In the IPM approach recommended soft pesticides are applied only as a last resort, when all non-chemical pest control tactics fail to protect the crop and the projected risks of crop damage and economic loss are serious.

3.12. POST-PRODUCTION (HARVEST AND POST-HARVEST) MANAGEMENT

Harvesting rice crops at the correct stage of grain maturity and the proper management of all operations after harvest are very important ways of preventing grain losses and preserving a high grain quality. It is also important to process rice by-products, such as rice bran, rice husks, etc., into valuable materials for use at home or for sale in local markets.

3.12.1. Improved methods of post-production (harvest and post-harvest) management

Post-production includes all of harvesting, bundling, hauling, threshing, cleaning, drying, storage, milling and grading of rice. Farmers need improved methods and/or machines (Fig. 29) to accomplish all of these activities in a manner which will prevent the very high grain losses (20 to 50%) that now occur from harvest to market. Improved post-production management methods will also enhance quality and germination percentage of rice seeds (from seed production cropping), and will allow farmers to obtain higher prices in markets.

- Harvesting: Harvest rice at the correct stage of maturity, i.e. when 80–85% of the panicles are straw colored and grains at the lower part of the panicles are hard and brittle to the bite.
- Threshing: Thresh the rice crop immediately after harvest to minimise grain damage by insects, birds, rodents, mold and attack by other seed pathogenic fungi. Manual threshing is common in countries like Cambodia, Laos and Myanmar. Farmers are encouraged to use portable threshers (Fig. 3.29) which will thresh and clean the grains at the same time.
- Cleaning: Clean manually threshed grains by repeated winnowing to remove chaff (unfilled grains) and other impurities.
- Drying: Dry the rice grains immediately after threshing and cleaning . This means reducing the moisture content to 14% for food grains and 12–13% for grains to be used for seeds. Delays in drying will cause quality deterioration (grain discoloration) and also physical losses. An immediate drying will preserve milling, cooking, odor, and eating quality of the milled rice. Dry the grains on a hard floor or on mats in open sunlight, or under ventilated plastic domes. Stir the grains at regular intervals so that the grains dry slowly and uniformly. Optimum temperature for drying will be < 60–65 ºC for food grains and < 43–45 ºC for grains to be used as seeds.
- Grains that are clean and dry store better and improve both the milling output and quality of the milled rice. Likewise, rice seed cleaning and drying will improve seed quality, storability, and increase crop yields when the seeds are planted in the following season.
- Grain storage: Improved grain storage at the farm level is critical for storing both grains and seeds for future use. Grains can be stored either in traditional woven plastic and burlap gunny sacks, or in sealed airtight storage containers. Air tight storage structures or containers prevent grains from re absorbing moisture from the surrounding air and/or rain, as well as reducing grain damage by pests during storage. Air tight (hermitic) storage is preferred for storing seeds till the following season.
- Milling: Milling is the final step in the post-production management of paddy. Rice milling efficiency depends on the entire post-harvest process from harvesting at the right crop maturity to drying and cleaning as described above. Millers prefer clean, dry [14% moisture content (MC)] paddy of a good quality for milling. The output of milled rice and its quality are highly affected by the milling process and the type of equipment used. Hand pounding of paddy is still practiced in some remote villages of Laos, Cambodia, Myanmar, Indonesia and Philippines. For mechanical milling three types of rice mill are used in Asia: (a) steel huller (Engelberg type); (b) under run disc sheller; and (c) rubber roller system as in modern rice mills. The first two types of mill are common in Asian villages and they operate using two stages: (i) removing husks from the paddy; and (ii) removing bran from the brown rice. The rural village mills are well maintained and skillfully operated in order to get a high output of good quality milled rice (Fig. 3.30).

Modern commercial mills have pre-cleaners and separators to clean and grade the paddy, rubber rollers to remove the husks and separate the brown rice from husks. Two separate whiteners and one polisher are used to remove the bran and polish the rice, and an electronic grader is used to grade the polished white rice grains.

The millng efficiency is indicated by the total output of milled rice (whole grains + brokens), per cent of milled whole grains (head rice), and overall quality of milled rice. The milling efficiency of different systems is shown in Table 3.3.

FIG. 3.29. Improved post-production management options for efficient harvesting, threshing, cleaning, drying, sealed storage, and milling of rice with minimal losses in grain quality and quantity (Source: www.knowledgebank.irri.org/).

(a) (b) (c)

FIG. 3.30. Both good quality paddy and efficient milling are prerequisites for high outputs of high quality milled rice: (a) Unhusked paddy rice; (b) Brown rice (after removing husks but retaining bran); and (Cc) Polished white rice (after removing both husks and bran and polishing) (Source: www.knowledgebank.irri.org/).

TABLE 3.3. MILLING EFFICIENCY OF DIFFERENT MILLING SYSTEMS [ALL VALUES EXPRESSED AS A PERCENTAGE (%)]

Milling process	Total husks + bran	Whole grains (Head rice)	Brokens	Head rice + brokens
Hand pounding with wooden mortar and pestle	40.0	40.0	20.0	60.0
Steel huller (Engleberg type)	36.6	46.5	16.9	63.4
Disc Sheller	32.5	55.9	11.6	67.5
Rubber roller	30.0	62.0	8.0	70.0

Data Source [44]

3.12.2. Rice preparations and rice by-products and their profitable use

This section describes various kinds of products that are made from rice or its by-product. The details of each such product are listed below:

- Wine like alcoholic beverages made from rice are commercially sold and consumed throughout Asia. The most popular rice drinks are sake in Japan, wang tsiu in People's Republic of China and a type of rice beer in the Ifugao region of the Philippines.
- Other popular rice products are: pre-cooked, canned, and puffed rice; rice flour; extrusion cooked rice based foods; rice puddings and breads; rice cakes and crackers; rice noodles and rice paper; fermented rice foods and vinegars; rice starch; and syrups.
- Rice straw is a valuable resource. It can be used as a dry fodder and/or a bedding material for farm animals, as a medium for growing mushrooms, as a fuel for cooking, as a roofing material for huts, or as a feedstock for composting with other household wastes. Instead of burning the rice straw (which causes air pollution), rice stubbles and straw are incorporated into the soil to maintain soil organic matter and increase soil potassium levels.
- Rice bran (which forms 5 to 8% of the grain weight) is a protein rich valuable feed for animals and chickens; it is also used as a dietary fiber rich food supplement, as a pickling medium, as a medium for growing mushrooms, and as a microbial growing medium for producing some enzymes. High quality bran from modern rice mills is also used to produce edible rice bran oil for cooking.
- Rice husks and hulls form about 20% of the grain weight. They are used as a fuel, a bedding, an incubation material for mushroom, a seedbed or potting medium for plant seedlings, or as a component of livestock feed. The husks and hulls are also used in concrete blocks, tiles, fiberboard, ceramics, cement and filters. They are rich in silicon and partially burnt rice husks are used as a silicon fertiliser (e.g. in Sri Lanka). Rice plants with adequate silicon content will be more resistant to insect pests and some

diseases. Fresh rice husks can be pressed into rice husk briquettes – forming a valuable biofuel with high caloric value for cooking in homes or in restaurants. Rice husks are also used for making pelletised compost from sewage sludge and other organic wastes in Japan.

3.13. APPROPRIATE MECHANIZATION

Rising wages and the decreasing availability of labor for farm operations are serious constraints to rice production in many developing countries. Appropriate mechanization is necessary for accomplishing certain farm operations efficiently, and in a timely manner. Mechanization is also essential for intensive rice farming. It is important to note, though, that most small holder farmers will not have enough capital to buy and own farm machines individually. In such cases, organizing farmers into producer groups will help them to acquire and manage farm machines for use by the group members. Alternatively, some well to do farmers can buy the machines and rent them to other farmers after their own needs are met. Simple farm machines that are most appropriate and useful for small holder rice farmers (Fig. 3.31) include: power tillers and 4 wheel tractors for land preparation, planter attachments and a drum seeder for planting in rows, rotating hoes (rotary and conical weeders) for weeding between rows of rice plants, sprayers to apply (ideally) bio pesticides, reapers for harvesting, mobile threshers for threshing and cleaning the grains, simple fans for manual cleaning of manually threshed grains, poly domes for drying grains, and simple sealed storage structures for storage of both grain and seed.

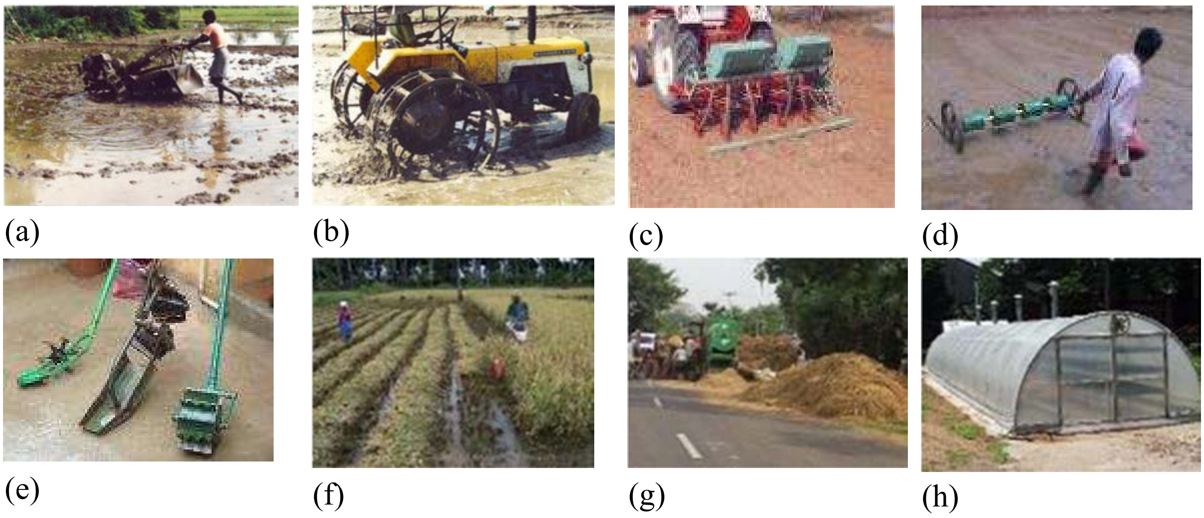


FIG. 3.31. Examples of appropriate mechanization: selected farm machines suitable for small holder farmers: (a) Power tiller; (b) Tractor with cage wheels; (c) Drill seeder cum fertiliser applicator; (d) Drum seeder; (e) Rotating hoe weeders; (f) Reaper harvester; (g) Mobile thresher; and (h) Plastic dome for drying rice grain (Photos by V. Balasubramanian).

3.14 REFERENCES CHAPTER 3

[1] BALASUBRAMANIAN, V., Reactive Nitrogen: Good, Bad and Ugly, Comprehensive Status Report (2010). SCON-ING, New Delhi, India, (2010) 1–52.

[2] GLOBAL RICE SCIENCE PATNERSHIP (GRISP), Rice Almanac, 4th Edition, International Rice Research Institute (IRRI), Los Banos, Philippines (2013) 283 pp. irri.org/resources/publications/books/rice-almanac-4th-edition

[3] HAEFELE, S.M., BOUMAN, B.A.M., Drought-prone rain-fed lowland rice in Asia: Limitations and management options. In: Drought frontiers in rice, (2009) 211–232.

[4] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FAO-Statistical Data Base (2015).

[5] JAT, M.L., SAHARAWAT, Y.S., GUPTA, R., Conservation agriculture in cereal systems of South Asia, Nutrient management perspectives, Karnataka, J. Agric. Sci. 24 (2011) 100–105.

[6] KEATING, B.A., et al., Eco-efficient agriculture, concepts, challenges and opportunities, Crop Sci. 50 (2010)109–119.

[7] FISCHER, G., et al., Climate change impacts on irrigation water requirements, Effects of mitigation, 1990–2080, Technol. Forecast. Soci. Chang. 74 (2007) 1083–1107.

[8] BHUIYAN, S.I., On-farm reservoir systems for rain-fed rice lands, International Rice Research Institute (IRRI), Los Baños, Philippines (1994) 164.

[9] SINGH, R.K., HOSSAIN, M., THAKUR, R., Boro rice, International Rice Research Institute (IRRI), India Office (2003) 234.

[10] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, The Future of Food and Agriculture: Trends and Changes, www.fao.org/3/a-i6583e.pdf (2017).

[11] WADE, L.J., et al., Nutrient requirements in rain-fed lowland rice, Field Crops Res. 64 (1999) 91–107.

[12] BOUMAN, B.A.M., et al., Yield and water use of irrigated tropical aerobic rice systems, Agric. Water Manag. 74 (2005) 87–105.

[13] TUONG, T.P., Productive water use in rice production, Opportunities and limitations, J. Crop Prod. 2 (1999) 241–264.

[14] FALKENMARK, M., ROCKSTROM, J., Balancing water for humans and nature, The new approach in ecohydrology, Earthscan, London, UK (2004) 247.

[15] LANG, N.T., et al., Rice breeding for grain quality in the Mekong Delta, OmonRice J. 19 (2013) 54–60.

[16] RAJENDRAN, R., et al., Nursery technology for early production of robust rice seedlings to transplant under integrated crop management, International Rice Research Notes 29 (2004) 73–75.

[17] BHADSAVLE, C.H., A zero-till conservation agriculture technique, Saguna Rural Foundation, Post Dahiwali, Maharashtra 410101, India (2015) 80 pp.

[18] SUBBAIAH, S.V., SREEDEVI, B., Efficacy of herbicide mixtures on weed control in direct-seeded rice under puddled condition, Indian J. Weed Sci. 32 (2000) 199–200.

[19] TUONG, T.P., BOUMAN, B.A.M., Rice production in water scarce environments. In: Kijne JW, Barker R, and Molden D (eds.), Water productivity in agriculture, Limits and opportunities for improvement, CABI Publishing, Wallingford, UK (2003).

[20] WASSMANN, R., et al., Characterization methane emissions from rice fields in Asia, Comparison among field sites in five countries, Nut. Cycl. Agroecosys. 58 (2000) 1–12.

[21] SHARMA, P.K., et al., Crop-water relations in rice-wheat cropping under different tillage systems and water management practices in a marginally sodic, medium-textured soil, In: Bouman B.A.M. et al. (eds.) Water-wise rice production, Los Baños, Philippines, International Rice Research Institute (IRRI) (2002) 223–235.

[22] SINGH, A.K., CHOUDHURY, B.U., BOUMAN, B.A.M., Effects of rice establishment methods on crop performance, water use, and mineral nitrogen, In: Bouman B.A.M. et al. (eds.), Water-wise rice production, International Rice Research Institute (IRRI), Los Baños, Philippines, (2002) 237–246.

[23] CHOUDHURY, B.U., BOUMAN, B.A.M., SINGH, A.K., Yield and water productivity of rice-wheat on raised beds at New Delhi, India, Field Crops Resol. 100 (2007) 229–239.

[24] MASSOUD, F.I., Basic principles for prognosis and monitoring of salinity and sodicity. In 'Proceedings of the International Conference on Managing Saline Water for Irrigation', held in Texas, 16–20 August 1976, Lubbock, Texas, USA: Texas Technical University (1977) 432–454.

[25] BALASUBRAMANIAN, V., ADHYA, T.K., LADHA, J.K., Enhancing Eco-Efficiency in the Intensive Cereal-based Systems of the Indo-Gangetic Plains. In: Issues in Tropical Agriculture, Eco-Efficiency, From Vision to Reality, CIAT, Cali, Columbia (2012).

[26] SUTTON, M.A., et al., Global overview of nutrient management, Centre for Ecology and Hydrology, on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative, Edinburg (2013) 1–6.

[27] MOHANTY, S.K., et al., Nitrogen deep-placement technologies for productivity, profitability, and environmental quality of rain-fed lowland rice systems. Nut. Cycl. Agroecos. 53 (1999) 43–57.

[28] BALASUBRAMANIAN, V., et al., Response of rice hybrid and an inbred variety to urea briquette deep placement in the Philippines, J. Agric. Res. Manag. 1 (2002) 50–60.

[29] BURESH, R. J., et al., The principles of site-specific nutrient management for rice, Poster paper presented at the IFA-FAO Agriculture Conference on 'Global Food Security and the Role of Sustainable Fertilization', Rome, Italy, 26–28 March 2003, IRRI, Los Baños, Philippines, (2003).

[30] DOBERMANN, A., WITT, C., DAWE, D., Increasing the productivity of intensive rice systems through site-specific nutrient management. Enfield, N.H. (USA) and Los Baños (Philippines), Science Publishers, Inc., and IRRI (2004) 410 pp.

[31] WITT, C., et al., Principles and promotion of site-specific nutrient management, 397–410. In: A. Doberman, C. Witt and D. Dawe (ed.), Increasing productivity of intensive rice systems through site-specific nutrient management, Enfield, NH, USA, International Rice Research Institute, Science Publishers Inc. and Los Baños, Philippines (2004).

[32] SINGH, YADVINDER., et al., On-farm evaluation of leaf colour chart for need-based nitrogen management in irrigated transplanted rice in north-western India. Nutr. Cycl. Agroecosys. 78 (2007) 167–176.

[33] VARINDERPAL, SINGH., et al., Evaluation of leaf colour chart for need-based nitrogen management in rice, maize, and wheat in north-western India. J. Res. Punj. Agric. Univ. 51 (2014) 239–245.

[34] SAHRAWAT, K.L., Iron toxicity in wetland rice and the role of other nutrients, J. Plant Nutr., 27 (2004) 1471–1504.

[35] JOHNSON, D.E., Weeds of rice in West Africa, Warda, Bouaké, Côte d'Ivoire, (1997) 312 pp.

[36] BALASUBRAMANIAN, V., HILL, J., Direct seeding of rice in Asia, Emerging issues and strategic research needs for the 21st Century, In: Pandey et al. (eds.) Direct Seeding: Research Strategies and Opportunities, International Rice Research Institute, Los Baños, Philippines 383 (2002) 15–39.

[37] WARDA, West African Rice Development Association, Africa Rice Center, WARDA annual reports, Benin, Cotonou (1998).

[38] BURKHILL, H.M., The Useful Plants of West Tropical Africa, Families A-D. Royal Botanic Gardens, Kew, UK 1 (1985).

[39] BURKHILL, H.M., The Useful Plants of West Tropical Africa, Families E-I. Royal Botanic Gardens, Kew, UK 2 (1994).

[40] HAEFELE, S.M., et al., Field screening of diverse rice genotypes for weed competitiveness in irrigated wetland ecosystems, Field Crops Res.88 (2004) 29–46.

[41] BALASUBRAMANIAN, V., et al., Increasing rice production in sub-Saharan Africa, Challenges and opportunities, Adv. Agron. 94 (2007) 55–133.

[42] CARSON, R., Silent Spring, A Mariner Book Houghton M1fflin Company, Boston & New York, USA (1962).

[43] PRETTY, J., BHARUCHA, Z.P., Integrated pest management for sustainable intensification agriculture in Asia and Africa, Insect. 6 (2015) 152–182.

[44] IRRI, Progress in upland rice research, Jakarta Conference, International Rice Research Institute (IRRI), Los Baňos, Philippines (1986).

4. PRODUCTION GUIDELINES FOR (RAINFED) UPLAND RICE BASED FARMING SYSTEMS IN ASIA

This chapter attempts to bring concise information package on 'improved' technologies on rice production under rainfed upland conditions and post-harvest procedures in different Asian countries.

FIG. 4.1. Upland rice ecosystem in Lao PDR [1].

4.1. INTRODUCTION – THE UPLANDS OF ASIA

Rainfed uplands are highly heterogeneous, with a climate ranging from humid to sub-humid, soils from relatively fertile to inherently very poor, the elevation from sea level to more than 2,500 m, and topography from flat/gently rolling to steeply sloping. On a top sequence, the plateau and sloping uplands are at the top, followed by rainfed and irrigated lowlands lower down, with flood prone lowlands in the valley bottoms. At the upland-lowland interface, the transition from uplands (drylands) to lowlands (wetlands) is often gradual and it may fluctuate from year to year, depending on variations in rainfall, rainwater runoff or availability irrigation water. If farmers can successfully control both irrigation and drainage, then they can choose to establish wetlands or uplands for rice cropping [1].

The upland rice (UR) ecosystem constitutes about 9.6% (14.5 mha) of the global physical rice area of 150 mha. There is 9 mha of UR in Asia, 3 mha in Latin America, and < 2 mha in Africa. All the upland rice ecosystems together contribute only 4% of the global rice supply. Important upland rice producing countries in Asia are India, Bangladesh, People's Republic of China, Indonesia, Thailand, Myanmar, Laos, Cambodia, Vietnam, and Japan.

Asian uplands, especially in the mountainous regions of South and South-East Asia, are characterised by their remoteness, low population density, poor or no rural infrastructure and poor accessibility. Most of the Asian upland soils are highly weathered and appreciably leached, often with low exchange capacity clays. Soils on the upper and middle slopes are generally well drained, shallow to deep, medium to fine textured and highly prone to erosion. Soils at the lower elevations are deep and fine textured. The isolated location of families and the small size of the villages, as well as the mountainous terrain, are believed to be the main cause of the extreme poverty in upland regions of Asia. The absence of roads makes it difficult for national governments to supply technical assistance and other inputs to farmers, and also for farmers to take their produce to markets.

4.1.1. Types of uplands in the mountainous regions of Asia

Based on their location in relation to streams and roads, and the degree of the slope, the uplands in mountainous regions of Asia (e.g. northern Laos and eastern India) can be divided into four categories:

- Favourable uplands which have a rolling topography with gentle slopes (less than 15%) and are found near streams, just above valley bottoms; some with well-formed terraces and fairly rich soils. These are high potential rice growing areas that can be used, with care, permanently for intensive, commercial rice production.
- Unfavourable uplands which are located on steep slopes (greater than 30%) and which have medium to poor soils. These upland areas are generally planted to non-rice crops such as maize, sesame, job's tear, etc. or left as fallows, for communal grazing of domestic animals. They are not suitable for intensive rice cropping.
- Uplands located near roads (and near streams) are often planted to commercial crops that have high market demand: pineapple, banana, papaya, vegetables, fruits, trees (teak), etc. Replacing upland rice with commercial horticultural crops or trees in these medium to high potential uplands may aggravate the expected problems of food scarcity and human nutrition in the near future.
- Remote uplands which have very difficult or no access to roads and thus markets. These uplands are less intensively cultivated, mainly by the slash and burn method (subsistence farming). Hunting and gathering is common, as is the collection and selling of non-timber forest products. These areas are inhabited by tribal communities and the incidence of poverty and child malnutrition is high in these remote upland areas.

4.2. AGRO-CLIMATIC CONDITIONS AND RICE GROWING SEASONS IN ASIAN UPLANDS

This section describes agro-climatic conditions of rice in Asia.

4.2.1. Amount and distribution of rainfall

In monsoon areas of Asia, the amount of rain and the duration of the rainy season vary not only between countries but also within countries. Upland rice is grown under heavy rainfall in Assam and West Bengal states and along the coastal areas of Kerala in India. However, it grows under low but variable rainfall conditions in Madhya Pradesh and eastern Uttar Pradesh.

The upland areas of Bangladesh are similar to the high rainfall areas of eastern India. The upland rice areas of northern Sri Lanka receive from 875 to 1000 mm of precipitation during 3 to 4 months of the year. In the upland areas of Burma, rainfall from May to November can be as low as 500 mm or as high as 2000 mm. In Indonesia, rainfall is uniformly distributed in the humid and semi-humid western regions. In contrast, the rainy season is very short and the rainfall is unevenly distributed in the eastern regions of Indonesia. Thailand's rainy season lasts from May to October, while in the Philippines, the upland areas experience both high and low rainfall patterns [2].

4.2.2. Day length (photoperiod)

Upland rice is generally planted during the periods when the day length is increasing in most Asian countries. Varieties which are insensitive to photoperiod are needed for use in areas where upland rice is planted when the days are becoming longer and flower initiation will thus occur under relatively long days. Photoperiod insensitive (i.e. day length neutral) rice varieties can be planted at any time of the year to suit local rainfall patterns and flower initiation and rapid development will occur at the end of the vegetative phase irrespective of the day length. In the regions of India where upland rice is planted at the beginning of monsoon rains in June, sensitivity to photoperiod with regard to rice flowering dates probably makes no difference [2].

4.2.3. Temperature

Most upland rice is grown in the plains, with high temperatures which range from 24 to 26°C. Low temperatures can be a problem, however, in the high altitude areas of India, Nepal, People's Republic of China, Japan Indonesia, northern Laos, Myanmar, and Vietnam [2]. Japanese workers have reported a positive association between drought tolerance and cold tolerance in rice [3], an attribute that is important for high altitude upland rice growing areas.

4.2.4. Upland rice growing seasons in different Asian countries

Local weather factors, particularly rainfall duration and distribution and temperature, determine the growing season for rainfed upland rice. Table 4.1 provides the upland rice growing seasons for selected countries of Asia.

TABLE 4.1. GROWING SEASONS FOR RAINFED UPLAND RICE IN SELECTED ASIAN COUNTRIES

Countries	Most common rainfed upland rice growing season
Bangladesh	Mar/May to Jul/Sep
People's Republic of China	May/Jun to Oct/Nov
India	Mar/Apr to Jul/Aug
Nepal	Apr/May to Aug/Sep
Sri Lanka	Sep/Oct to Jan/Feb
Indonesia	Nov/Dec to Apr/May
Philippines	Jun/Aug to Nov/Dec
Myanmar	May/Jun to Oct/Nov
Thailand	May/Jun to Sep/Oct
Vietnam	Apr/May to Aug/Sep

4.3. SOILS OF ASIAN UPLANDS

In South and Southeast Asia, the major soils of the unterraced sloping land, where most upland rice is grown, are ultisols and alfisols, with some oxisols in limited areas [2, 4].

Ultisols are much more common, particularly in the Sumatra and Kalimantan areas of Indonesia, and also in Thailand. These soils have a sandy texture on the surface, but subsoils tend to have more clay. The clay fraction is dominated by kaolinite clay that is common in hot, moist climates—for example in tropical rainforest areas. It is produced by the chemical weathering of aluminium silicate minerals like feldspar. It is often coloured orange red by iron oxide. Kaolinite has a low shrink swell capacity on drying and wetting and a low cation exchange capacity, with a low base saturation. The shallow surface layer of soil for the ultisols is easy to cultivate, but is more prone to erosion during a heavy rainfall than many other soil types; i.e. the surface soil becomes saturated, causing a runoff of excess water from sloping areas.

Alfisols have more clay (including montmorillonite clay that has high shrink swell capacity) in the B horizon (subsoil) than in the A horizon (surface soil). Their base saturation is high. Alfisols are more common in very dry zones and are easy to till because of their typically granular surface soil structure. These soils have a high capacity to retain rainfall because the more clayey B horizon retards losses by percolation.

Oxisols cover only minor areas of upland rice in Southeast Asia. They are found at lower elevations in Sarawak (Malaysia) and in the mountainous Ban Me Thuot area of South Vietnam [5]. Oxisols are the most important rice soils on Java Island, though they are locally classified as latosols. Oxisols in Southeast Asia are found on materials originally derived from volcanic rocks. These are highly weathered soils with few textural changes throughout the profile. Oxisols are high in clay content, mostly kaolinite type cay with oxides of iron and aluminum. However, they have only small proportions of water dispersible clay, and thus usually have high water infiltration rates. The oxisol soils are acidic in many upland rice areas of Southeast Asia. The soil pH in Ban Me Thuot, Vietnam, and in Batangas, Philippines is low, ranging from 4.5 to 5.8. In fact, most upland soils of Asia have a similar pH range.

Soil moisture stress and associated problems like surface soil sealing, poor germination of seeds, poor emergence of seedlings, and excessive weed growth are common. The chemical composition and nutrient status of the aerobic upland rice soils include: Fe deficiency and a low availability for N, P, and Si on all soils. There is also Mn and Al toxicity in acid soils. Under aerobic and acidic soil conditions, P fixation (binding) is high and thus P availability to crops is low for most upland soils. Unlike the low availability of P, Fe and Mn, zinc (Zn) is more readily available in upland than in lowland submerged soils. However, as most of the Zn is concentrated in the upper soil horizons, any erosion of the surface soil horizon will accentuate Zn deficiency in upland rice crops [2].

4.4. UPLAND RICE FARMING SYSTEMS

Upland farmers have two types of land holdings: (a) crop lands and (b) gardens. The typical upland holding consists of both cropped and fallow (1 to 3 years) fields. Garden lands are subdivided into three types: (b) home gardens, (c) river gardens and (d) tree plantation gardens. Home gardens are located near the house, while river gardens are narrow strips of land along the river bank (Fig. 4.2. It is noted that not every household has a river garden.

(a) (b) (c) (d)

FIG. 4.2. Examples of farmers' land holdings in the northern uplands of Laos: (a) upland lowland continuum, (b) home gardens, (c) river gardens, and (d) tree plantation gardens [92].

Rainfed upland rice is grown much like wheat or maize in unbounded or bounded fields. Rice fields are located on level, gently rolling, or steeply sloping topography, at elevations up to 2400 meters and with annual rainfall ranging from 1000 to 4500 mm. Uplands rice is grown on highly fertile to highly weathered, infertile acidic soils. Only 15% of total upland rice is grown on fertile soils. Rainfed upland rice is cultivated under a variety of farming conditions – in shifting cultivation, in continually dry fields, and in alternating dry and wet fields (where rice begins as an upland crop and is harvested as a wetland crop). As a result, rainfed UR grain yields are highly variable from less than 1 t ha^{-1} to more than 2.5 t ha^{-1}, with the overall mean yield being 1 t ha^{-1}. However, yields for upland rice can be increased by the development and use of improved varieties and by cultural practices designed to suit the local soil, climatic, and social conditions in different regions.

4.4.1. Traditional slash and burn shifting rice cultivation

Earlier, when villages were small and population density was low, 1–2 years of shifting cultivation with long (> 15 years) fallow periods was historically the dominant land use system. Farmers grew upland rice either as a single crop, or rice mixed with other crops on mid slopes, using slash and burn methods (Fig. 4.3) [7]. For example, in Laos in 1990, an estimated 2.1 mha of uplands were under this type of shifting cultivation, with an annual cropped area of roughly 250 000 ha. This meant 1.8 mha was placed in regenerating bush fallows of varying length (1–19 years). In most mountainous regions of Asia there has been with their national government's tacit support plus incentives, extensive deforestation, followed by removal of plant cover. Large concessions of land have been given for industrial plantations, or for mining. These changes, together with shortened fallow periods have all contributed to the destruction of upland landscapes. They have also resulted in increased soil erosion, nutrient depleted and dried out soils, decimated soil organic matter, reduced soil microbial diversity, and an increase in infestation by weeds. As a result, upland areas planted to rice have diminished, and upland rice yields have steadily declined in Asia.

FIG. 4.3. Traditional slash and burn cultivation of upland rice, Northern Laos [6]

In traditional shifting cultivation, the brush is cleared from the land, the land is then ploughed once or twice, and rice seeds are broadcast or dibbled (with the help of a dibble stick). Weeds are removed as and when necessary and mature rice panicles are harvested – all accomplished manually over a long period of 10 months for each year's crop.

With increasing human population pressure being put on the land and the various national governments' new land use policy to reduce fallow periods to 3–4 years between cropping, upland farmers are being forced to abandon their traditional shifting cultivation practices, which included long fallow periods. However, improvements have been suggested to replace shifting cultivation practices, including: permanent upland rice based farming systems; growing upland rice between rows of perennials including trees (agroforestry) or between contour planted live hedges; using reduced or zero tillage and crop residue management; adopting mixed or relay cropping to keep the vegetation cover over the soil for longer periods – up to most of the year; the addition of plant ash instead of expensive lime to reduce soil acidity; and incorporating leguminous trees (e.g. *Acioa barterii*) within upland rice farms – the latter bringing up cations from subsoil layers to the surface soil through leaf litter.

4.4.2. Permanent diversified upland rice based farming systems

With use of the above measures, shifting cultivation with 3–5 year fallow periods now accounts for 14% of the Asian upland rice area, mainly in north eastern India, Lao PDR and Vietnam. Some 70% of the upland rice areas have instead become permanent diversified farming systems, ones where rice is grown every year and is closely integrated with other crops and livestock [1].

Among the four types of uplands (Section 3.4), the favorable uplands, which are situated on slopes less than 15%, and found near streams or just above valleys, are the most suitable habitats for continuous rice cultivation. Soils in some of these uplands are fairly rich in organic matter and nutrients. These high potential areas can thus be used for permanent intensive and commercial rice production [8]. However, to secure a sustainable productivity of upland rice under permanent cultivation, upland farmers utilise suitable cropping systems, like the rotation of the rice crop with other crops, multiple cropping, intercropping, mixed cropping, and alley cropping [9]. In locally adapted upland rice based cropping systems, crop yields, cropping intensity, and monetary returns increase, while risks of crop failure due to climate change or market swings are reduced substantially. Moreover, family nutrition and cash flow improves, due to increased availability of a mix of agricultural products for self-consumption or for sale. Soil fertility is being enhanced by increased addition of crop residues, including N-rich legume residues. Even so, addition of organic manures and or composts and some amount of mineral fertilisers is necessary to maintain high yields of different crops in intensive upland rice based cropping systems.

Crop rotation: Upland rice is rotated with other crops such as maize, sorghum, beans, pigeon pea, mustard, Bengal gram, or safflower. The rotation of crops is one of the best ways to slow down or prevent the buildup of weeds, insect pests and diseases. In alternate years, upland fields are left fallow, or planted with green manure legumes like sunhemp, mucuna, sesbania or fodder legumes such as daincha. Such crop rotations will help build up soil fertility and reduce weed pressure in upland rice farms. Adequate nutrition of different crops in rotation is of course critical to maintain crop yields [10].

Intercropping: Planting 2 to 3 different crops in separate rows is defined as intercropping. Upland rice is often intercropped with legumes such as pigeon pea, green gram, black gram, soy bean, or groundnut; with finger millet, maize, sunflower, or cassava [10]; and with maize, cocoa, or poplar trees (Fig. 4.4). For example, in the upland rice pigeon pea systems, farmers can plant one row of pigeon pea for every 10 rows of rice in row seeded crops [11]. Dry pigeon pea grains constitute a protein rich diet while pigeon pea residues will enrich the soil with organic matter and biologically fixed N.

(a) (b) (c) (d)

FIG. 4.4. Upland rice-based intercropping systems: (a) Rice-green gram; (b) Rice-maize; (c) Rice-cocoa; and (d) Rice-poplar trees (Source: 37a: [10]; 37b, c, d: By. V. Balasubramanian).

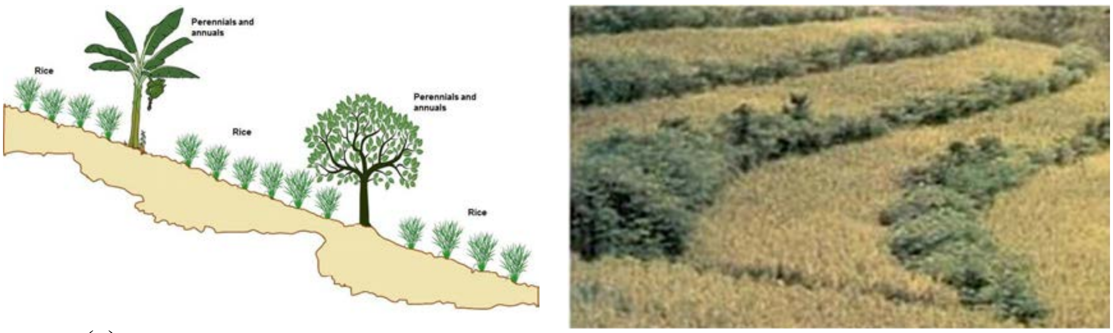
Mixed cropping: Mixed cropping refers to growing two or more crops simultaneously in the same field with no distinct row arrangement. This practice maximises land productivity, acts as an insurance against total crop failure, supplies multiple products for family consumption, provides a longer lasting vegetation cover to soil, and reduces pest pressure due to increases in on farm biodiversity. Crops planted in random mixture with upland rice include: maize, sorghum, millets, job's tear, sesame, cowpea, groundnut, pigeon pea, okra, yam, cocoyam, cassava, sweet potato, etc. [10]. For example, in upland rice pigeon pea systems in Laos, farmers mix rice seed (90%) with pigeon pea seed (10%) and broadcast the seed uniformly to establish mixed crops [11]. Crops are harvested as and when they mature. Use of judicious crop combinations, adequate fertilisation and weed control are necessary to maintain high yields of different crops over time.

Planting upland rice and other annual crops between rows of perennials or tree crops: Upland rice is grown between rows of perennial crops such as banana, rubber, oil palm, coconut or cocoa during the establishment stages of the perennials, especially in Indonesia, Philippines and in parts of India. No crop is planted when the perennial crops grow and shade the ground completely. Only certain crops like banana, plantain, colocasia, yam and fodder sorghum or maize can be grown in fully developed tree plantations (Fig. 4.5).

(a) (b) (c)

FIG. 4.5. Annual crops planted between rows of coconut trees in Tamil Nadu, India: (a) banana, (b) colocasia, and (c) fodder sorghum or maize [6].

Growing upland rice on sloping lands: On steeply sloping lands (slope > 30%), no rice or annual crops are planted; rather these lands can be covered by planted forests. On other lands with a slope less than 30%, food crops like upland rice is kept to a minimum, just enough to meet subsistence needs. The remaining land can be left under perennial forage crops and or pasture for raising farm animals. Areas with a gentle slope and shallow to medium deep soils is selected for growing annual crops like upland rice; here again, rows of perennials, including trees, are planted along the contour to prevent soil erosion and to facilitate infiltration of rainwater into the soil (Fig. 4.6). Alternate crops like banana, plantain, and yam can be grown under partial shade of trees on slopes [10].



(a) (b)

FIG.4.6. Improved upland rice systems on sloping lands: (a) Agroforestry systems in which rice is grown between rows of perennials including trees and annuals; and (b) Upland rice growing between permanent live hedges established along contours of sloping uplands [10].

Conservation agriculture practices for upland rice farming: Cropping systems, based on direct seeding on permanent plant cover without soil tillage, seem to be a promising technique to tackle the challenges of soil and water conservation and environmental protection that traditional upland agriculture is facing in the tropics. Conservation agriculture (CA) practices like reduced or zero tillage and crop residue management will help farmers cultivate rice sustainably. Here, a planting stick is used to make holes on land covered with previous crop residues and rice seeds are dropped into the holes and covered with soil. Alternatively, a continuous slit is opened in rows and seeds are placed and covered with soil, leaving the remaining land undisturbed. Weeds are often controlled by herbicides in zero till plots. In addition, adopting relay cropping will help keep the vegetation cover over the soil for longer periods or most part of the year [10].

Garden land farming: Garden lands near houses are used for vegetables (chili, cucumber, cabbage and coriander), cash crops (banana, pineapple, onion), and also for raising farm animals. River gardens are used mostly during the dry season when the water level in the river is low, exposing fertile strips where vegetable crops grow well. Fish are caught from the rivers for home consumption and for sale. On deep soils, farmers develop plantation gardens, where they plant teak, rubber, and or paper mulberry [6].

4.5. RICE PRODUCTION CONSTRAINTS IN RAINFED UPLAND RICE ECOSYSTEMS

Biophysical constraints: Short fallow period rainfed upland rice farming systems experience a great number of abiotic stresses and a high degree of uncertainty in the timing (arrival and ending of rains), and duration and intensity of rainfall. Uncertain rainfall patterns impose water related stresses on seed germination, seedling emergence and crop growth as well as weed infestation in upland rice fields. In addition, land preparation and crop management operations are either delayed or skipped, which can result in severe grain yield losses. Unfavorably low temperatures limit upland rice yields in high altitude areas. Soil related problems include a low, but highly variable, soil fertility; soil acidity; nutrient toxicity; and soil erosion. Biological constraints include weeds, blast disease, brown spot, stem borer, rice bug, and rats (Fig. 7). Nematodes are a serious problem in continuously mono cropped upland rice fields [12, 13] and can reduce yields by up to 30%. Termites are also a problem in some areas and rodents and birds damage rice crops in all ecosystems including uplands.

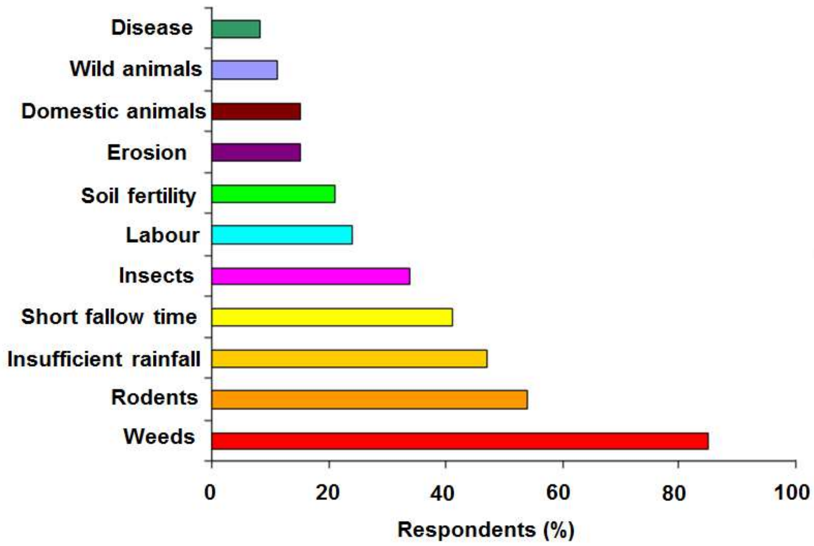


FIG. 4.7. Farmer perceived problems and constraints to production of upland rice in the northern region of Lao PDR [6].

Socioeconomic constraints: include remote location of villages and poor rural infrastructure, a lack of processing, storage, transportation and marketing facilities; insufficient land holding or poor title to land; a labour shortage due to outmigration of youth to cities; and increasing human population pressure on limited and fragile natural resources.

Management constraints: Poor land configuration (ridges and furrows), absence of contoured live hedges or barriers to soil movement; improper tillage and absence of soil cover (mulch), which then leads to soil erosion and loss of soil moisture; removal of trees from farms a process that can aggravate high temperature effects on crops and reduce the addition of tree leaves that can enrich soil organic matter; use of poor quality seeds and improper planting or seeding methods; poor weed control; the 'mining' of soil nutrients due to inadequate addition of organic manures and/or fertilisers; and a continuous mono cropping with rice.

Human resource constraints: The main problem here is the inadequate education of upland rice farmers. An increasingly ineffective agricultural extension service and poor support systems hamper the promotion and development of sustainable upland agricultural production systems. Other human resource related constraints are:

- Weak or non-existent research extension farmer linkage, especially in Cambodia, Laos, Myanmar and Nepal.
- Inadequate or no farmer organizations that can command and receive farm credits, crop insurance and other inputs and support for profitable upland farming systems.
- Lack of public private partnerships for enhancing rice production, processing and value addition in rural areas through, for example, contract farming or other arrangements.
- Reduced labour availability for farming due to out migration of rural youth to cities in search of better jobs

4.6. IMPROVED UPLAND RICE CULTIVATION

Annual rice cropping is possible only in the favorable uplands which are situated on slopes less than 15%, mostly near streams or just above valleys, and are endowed with soils that are fairly rich in organic matter and nutrients. These high potential areas can thus be used for permanent intensive and commercial rice production [8]. In some 70% of the upland rice areas of Asia, the land has been modified suitably by terracing and other methods for permanent diversified farming systems, in which rice is grown every year and is closely integrated with other crops and livestock [1].

4.6.1. Configuring land for rice cultivation (Yunnan Model)

Farmers form flat terraces (Fig. 4.8 a,b) on valley edges and gently sloping lands to effectively capture and use rainwater for rice cultivation. Perennial vegetation strips are then developed between terraces to moderate the above ground water flows and reduce soil erosion during rains. The flat nature of a terrace also makes it easier to use a hand tractor and other small farm machines to cultivate rice and other crops.

(a) (b)

FIG. 4.8. Terraced rice fields on gentle slopes (favourable uplands) in Laos, contrasted with terraced fields (a) and Steep slopes in Guangxi, People's Republic of China (b) (Source: 8a, by V. Balasubramanian).

4.6.2. Selection of upland rice varieties

Most traditional tropical upland rice varieties are of a tall type, moderately early maturing, low tilling with short firm (bulky) grains, and generally tolerant to drought. A few varieties have high tilling ability and slender grains. These traditional rice varieties also have long vegetative phases and flower only under long day lengths (photoperiod sensitive). Most upland rice varieties, although adapted to a low soil moisture regime, are also influenced by the intermittent and erratic nature of rain events, since farmers have no means of storing water for use in their fields.

Improved rice crop varieties selected for upland cultivation are recommended to have high tolerance to soil acidity and to Mn and Al toxicity. The traits of tolerance to drought and low soil fertility as well as resistance to local insect pests and diseases (specifically blast disease), and to lodging, is incorporated in high yielding upland rice varieties. In addition to the above characteristics, rice varieties selected for high altitude uplands (drylands) is an enhanced tolerance to cold, which is also linked to tolerance to drought [3]. Rice varieties for areas with short rainy season (3 to 4 months) have a growth duration of 90 to 110 days while medium to long growth duration (125 to 150 days) rice varieties are needed for areas with longer rainy season (5 to 7 months).

A dual-purpose type of early maturing rice varieties, adapted to both upland and lowland rice culture, includes Dular (from Bangladesh and India) and Bluebonnet 50 (bred as a lowland type in the U.S. but also grown as an upland variety in South America). A few modern hybrids, such as C 22 from the Philippines, are high tilling and moderately tall. Other varieties, adapted to combinations of both upland and rainfed lowland rice cultures (such as gogo, rantjah and beasi farming systems in Indonesia), have many lowland features. The upland varieties of Japan, on the other hand, differ distinctly from the lowland types: they are taller, and have fewer tillers, thicker culms, longer and broader leaves, and deeper roots. Their panicles, as well as their grains, are longer. They are generally more resistant to drought and the blast disease, but are less responsive to applied nitrogen [14]. Upland rice breeding workers in Brazil and at the Yunnan Academy of Agricultural Sciences (YAAS) in People's Republic of China are trying to develop F1 rice hybrids for upland rice culture in high elevation areas (cold tolerance) and water scarce areas (drought tolerance).

A range of new upland rice varieties are needed to suit the highly diverse environments in which upland rice is grown in Asia. Rice breeders in different Asian countries, in collaboration with International Rice Research Institute (IRRI) scientists, have developed two types of improved rice varieties for cultivation on the more favorable uplands (Table 4.2): Improved (glutinous and non-glutinous) local rice varieties (Fig. 4.9a) and improved photo insensitive, input responsive high yielding rice varieties (Fig 4.9b). In People's Republic of China, for example, two high yielding upland rice varieties, viz., Yunlu 29 and Yunlu 52 with a yield potential of 6.4 t ha^{-1} (or higher) have been released for cultivation in Yunnan Province [15].

(a) (b)

FIG. 4.9. (a) Improved, farmer preferred, sticky local upland rice varieties; and (b) introduced, non-sticky upland rice varieties with short stalks and high yields as in Lao PDR [6].

TABLE 4.2. A LIST OF ASIAN UPLND RICE VARIETIES: IMPROVED LOCAL STICKY AND NON-STICKY RICE VARIETIES AND INPUT RESPONSIVE, HIGH YIELDING AEROBIC RICE VARIETIES (HYVs) CULTIVATED IN SELECTED ASIAN COUNTRIES (THIS IS NOT AN EXHAUSTIVE LIST OF VARIETIES)

Countries	Improved local rice varieties	Improved high-yielding aerobic rice varieties
Bangladesh	Kataktara (DA2), Panbira (DA12), Dharial (DA14), Dular (DA22 adapted to both upland & lowland), Marichbati (DA24), Hashikalmi (DA26)	IR8
Bhutan	Jangkhar, Kamsing	IR8
Cambodia	Cammalis, Phka Kheni, Phka Malis, Red rice (sticky)	IR8
People's Republic of China	Local upland varieties	HYVs: Yunlu 29 & Yunlu 52 (yield: 6.4 t ha^{-1}); IRAT 104, Luyin 46 (B6144F-MR-6)
India	Kiran, Kanchan, Gora types, Huskalam, Mangala, Rasi, Pragathi, Doddi, Subhadra, Pallavi, Sathi, Lalnakanda, Avlyan, Poorgar, Norungan, Bala, Anjana, Dular, Kiron, Chall, Aswanloaya, Manoharsali	IR 8, IR 20, IR43, IR45, IR5-47-3, GMR-17, A200, N22, Hamsa, CR 1014, CR 1046, CR 1057, TKM 6, CO31, Karuna, Anna 4, Majhosa 3, VN Dhan 206, Rasi, NC 1626, Jhona 351, Lalnakanda 41, Ratna
Japan	Improved tall local varieties with fewer tillers, thicker culms, longer and broader leaves, longer panicles and grains, and deeper roots.	Improved upland rice varieties that are tolerant to cold and drought.
Lao PDR	Sticky rice: *Nok, Makhinsoung, Chau Mad, Non, and Laboun (yields ~2 t ha^{-1}, with* a harvest index of 0.30 to 0.35). Non-sticky rice: *Chao Do, Chao Khor, Phasou-1, Mak Nye (Asian gall midge resistant) (yields > 2 t ha^{-1}, with* a harvest index of 0.30 to 0.35)	*B6144F-MR-6 and IR55423*-1 (Yields 3.5 to 4.0 t ha^{-1}, long slender grains); *Apo* (Yields up to 5 t ha^{-1}, drought tolerant)
Indonesia	Sontani, Sagi, Semaritl, Seartus Malan, Ganjah Lampung, Pulut Nangka, Kartuna, Bicol, Gata, gall, Gemar, Acehnese rice; Gogorantja & Beasi (adapted to both upland and lowland)	BPI-76-1, IR8, IR43, IR45

Myanmar	Paw San, Emata, Loonzain, Nagasein	
Nepal	Sookha dhan	IR 8, IRAT 104
Philippines	Pinuloi, Klnandang Pull, Aposiol, Palawan, Azucena, Dinalaga, Kinandang Patong	Milpal 4, HBDA-2, BPI-1-48, Azil 26, C22 (hybrid rice), UPL RI-3, UPL RI-7, IR8, IR43, IR45, IR 5411, IR64 + DRO1 rice (drought tolerant IR 64))
Thailand	Khi Cang, Goo Muang, Dawk Payom, Sew Mae Jan, Ble Chal, Sew Khao, Sew Dam, Sew, Niew Sun Pah Tong, Leb Nok Pattani (good for noodles).	KDML 105 (Blast resistant)
Vietnam	Ha-Lan, Bao Thai	KU 84, KU 96, C 22, BG 35-2, IR1561

Data Sources: [1, 2, 10, 15]

4.6.3. Clean and good quality seed

Upland rice farmers can buy high quality seeds of locally adapted improved rice varieties, if available, or use their own seeds for planting. In a well cultivated upland rice field, farmers can select large panicles with well filled grains and thresh them separately, then clean and dry the seeds for use in the next planting.

4.6.4. Land preparation

Timely land preparation and planting is necessary to take full advantage of the rainy season and thus obtain high yields. Upland farmers practice reduced or zero tillage (especially on steep slopes where machines cannot be used to prepare the land) and dry tillage.

Reduced or zero tillage

Conservation agriculture (CA) practices like reduced or zero tillage and ground cover management with crop residues will help cultivate upland rice sustainably. In subsistence farming, a planting stick is used to make holes on land covered with previous crop’s residues and rice seeds dropped inside the holes and covered with soil. Alternatively, a continuous slit is opened in rows 20 cm apart manually or with a machine (seeder) and seeds are placed and covered with soil, leaving the remaining land undisturbed. Weeds are often controlled by herbicides in zero till plots.

Dry tillage

The methods are similar to preparing land for crops like maize, soybean or wheat. The details are as follows:

- An animal drawn plough, a hand held tractor, or a four wheel motorised tractor can be used for land preparation. Till the field when the soil is moist and friable (Fig. 4.10a).
- Spread out and incorporate into the soil all residues from the previous crop and the weeds that have grown during the fallow period. In addition, farmers can apply organic manure and or compost and incorporate it into the soil during the first plowing.
- After the first ploughing, the fields will appear rough with large clods (Fig. 4.10b)
- Wait for the first rains and allow 15 days for weed seeds to germinate and for organic matter to decompose in moist soil.
- Apply (broadcast uniformly) lime or plant ash to reduce soil acidity and a phosphorus fertiliser prior to the 2nd ploughing.
- Plough for 2nd time to uproot the germinated weeds, then harrow and finally level the soil under dry condition (Fig. 4.10c).

- Alternatively, a tractor with an attached rotovator can be used to till and level the soil (Fig. 4.10d). Field levelling is very important for obtaining a good germination of seeds and a uniform emergence of seedlings throughout the field.

(a) (b) (c) (d)

FIG. 4.10. Dry land preparation: (a) First ploughing; (b) Appearance of the soil with large clods just after primary tillage; (c) Well prepared dry soil after harrowing and levelling, ready for dry seeding; and (d) Using a rotovator for preparing dry or moist soil for dry seeeding (Photos by V. Balasubramanian).

4.6.5. Dry direct seeding

Dry direct seeding (DDS) onto dry soil is practiced on level or slightly undulating lands. The best time for DDS is when there is a strong probability for sufficient rains to occur, within a week, to soak the soil. Dry seeds sown before the start of the rains germinate and grow quickly after early rains [16]. The details of dry direct seeding follow:

- Uniformly broadcast seed at a rate of 80 to 120 kg ha^{-1} (Fig. 4.11a) onto a dry or moist soil.
- Harrow the field after broadcast seeding to lightly cover the seeds with soil, manually using a rake or by a tractor drawn rake or harrow (Fig. 4.11b).
- The depth of seeding is critical for upland rice. Seeding depth is determined by the seed size and the physical condition of the soil – smooth and level seed bed with fine clods, low soil bulk density, and good soil moisture status. The optimum seeding depth is 1 cm to 2 or 3 cm for most upland rice varieties.

- Farmers can also sow the seeds behind a plough (Fig. 4.11c) or drill the seeds with a seed-cum-fertiliser drill (Fig. 4.11d) at a seeding rate of 40 to 60 kg ha^{-1}, if they wish to plant in rows. The optimum row to row spacing is 20 cm to 25 cm.
- With sufficient early rains, seeds will germinate and seedlings start to emerge from the ground. Optimum crop emergence is indicated when 333 seedlings emerge per square meter.

(a) (b) (c) (d)

FIG. 4.11. Dry direct seeding: (a) Sowing seeds by broadcasting and (b) Harrowing to cover the seeds with soil; (c) sowing the seeds behind a plough for seeding in rows; and (d) Seed-cum-fertiliser drill for dry seeding (Source: www.knowledgebank.irri.org/).

4.6.6. Rainfall capture and soil moisture conservation techniques (a top priority for stable yields in uplands)

For all rice varieties the water requirement is the highest during the reproductive phase (from panicle initiation to heading), and during this period rice fields must have 2 to 5 cm of standing water. Any moisture deficit (due to drought) during this critical period will seriously affect spikelet formation and grain filling, resulting in a drastic reduction in yield, or even a complete crop failure. This section highlights strategies to conserve soil water for its efficient use.

- Avoid burning of crop residues – instead incorporate them into the soil to increase soil organic matter content and soil moisture retention capacity.
- Wherever possible, farmers also use dry plant residues to mulch and cover the soil between rows of rice plants in order to conserve soil moisture and to suppress weeds (Fig. 4.12).
- The development of natural or cultivated vegetation strips, or stone bunds at regular intervals across the slope, or between terraces, will help enhance rainwater infiltration into the soil.
- Forming flat terraces on gently sloping, favorable uplands is also useful.
- Wherever possible, farmers dig ponds in their farms to collect rainwater and use it for life saving emergency irrigation by sprinkler to save the crop during periods of drought. However, this option is very limited for most upland farmers.

FIG. 4.12. Mulching with crop residues will help to conserve soil moisture and also help to suppress weeds (Photo by V. Balasubramanian).

4.6.7. Improving soil fertility and reducing soil erosion

Protecting the soils against wind and water erosion and maintaining soil fertility are important steps towards developing sustainable rice production systems.

- Soil plays a key role in providing essential nutrients and water for rice growth; however poor or inappropriate farming practices may lead to nutrient mining and depleted soil fertility and ultimately lower rice productivity. The following section describes how to maintain and if possible improve soil fertility to make soil more resilient against climate change and minimise its degradation. In alternate years, rotate upland rice with planted legumes (e.g. pigeon pea, stylosanthes) or non-legumes (e.g. paper mulberry), or fallow the field – all will help to improve soil fertility [17].
- Apply all animal manure and or compost before the first ploughing and incorporate it into the soil with the first ploughing.
- Farmers can also apply, if available or affordable, lime or plant ash to reduce soil acidity just before the first ploughing.
- In areas with a high potential for growing upland rice, i.e. lands with deep fertile soils or terraced flat fields, farmers apply a moderate rate of N (40 to 60 kg N ha^{-1}) and some P (9 kg P ha^{-1}) in order to get high grain yields (3 to 4 t ha^{-1}) if input responsive, high yielding upland rice varieties are used.
- Micro dosing of fertilisers: Farmers can place fertilisers by hand into small holes (2 to 3 cm diameter and 4 to 5 cm deep) at regular intervals for applying small quantities of fertilisers.
- However, fertilisers are applied only when rainfall is expected to be good and high yields (from fertiliser responsive varieties) can be predicted with reasonable certainty.

4.6.8. Reducing weed infestation

Weed such as grasses, sedges, and broad leaf weeds compete with upland rice crops for water, light, and nutrients, thereby reducing rice yields [13, 6, 18, 19]. The following farm practices ensure to reduce the negative impacts of weed on rice productivity.

- Rice crop rotation with planted fallows and/or in situ mulching between rows of rice plants (Fig. 4.12) will help to reduce weeds problems [20].
- Farmers can also plant weed competitive rice varieties, ones that have vigorous early growth, thereby covering the soil quickly. Good examples are NERICA type rice varieties developed for African uplands [3, 21].
- Good land preparation and use of clean rice seed (free from weed seeds) will also minimise weed problems.
- Farmers can manually remove young weeds 20 to 25 days after seeding (DAS). A second weeding may need to be done 30 to 35 DAS.
- Inter row cultivation: Farmers harrow the soil between rice rows with a rake or an animal drawn harrow (Fig. 4.13) to stir the soil and to control weeds at early stages (20 to 25 DAS)
- In imperata weed infested fields, planting a dense ground cover like mucuna in fallow years is necessary to reduce the density of the imperata weed in future cropping years [15].
- Chemical weed control: Small holder upland farmers rarely use herbicides to control weeds. In intensive cropping of upland rice on fertile soils in high potential uplands, farmers may apply suitable herbicides to control weeds. Herbicides will also be needed to control weeds in zero till rice cultivation.

(a)

(b)

FIG. 4.13. Harrowing with a rake (a) in Odisha, India and with an animal-drawn harrow (b) in the Philippines to control weeds in direct seeded rice in rows [2, 10].

4.6.9. Controlling pests and diseases

This section describes the major insects, pests and diseases of the upland rice system and the integrated management control to minimise their damaging effect on rice productivity. Major insects and other pests of upland rice are root aphid, Asian gall midge, stem borers, rice bugs, nematodes, termites, rodents, and birds. Important diseases include blast, grain discoloration, and grain/kernel smut. Adopting integrated pest management (IPM) can be an economical method for upland rice farmers to control pests and diseases. These include:

- During the first ploughing farmers bury crop residues and stubbles which can harbor eggs and or larvae of stem borers.
- Farmers plant resistant rice varieties to minimise the impacts of insect pests and diseases. Blast resistant upland rice varieties are now available.

- The use of clean, healthy seeds will help prevent seed borne diseases.
- Farmers can also increase seeding rate per hectare to compensate for loss of seeds by ants or birds.
- Micro dosing and applying of nitrogen fertilisers in 2 to 3 split applications will help to reduce certain insect pests, such as the brown plant hopper and Asian gall midge.
- Mechanical or hand removal of disease infested plants is the most effective cultural control method.
- Intercropping or the mixed planting of rice with other crops (like Job's tears or pigeon pea) will help to reduce bird damage and also help to control blast disease outbreaks in upland rice.
- Rotation of upland rice with non-rice crops, or use of fallows in alternate years [22], will help to break the life cycle of most insect pests.

4.6.10. Harvesting and post-harvest processing

Post-production includes all of harvesting, bundling, hauling, threshing, cleaning, drying, storage, milling and grading of rice. Farmers need improved methods and/or machines to accomplish all of these activities in a manner which will prevent the very high grain losses (20 to 50%) that now occur from harvest to market. Improved post-production management methods will also enhance quality and germination percentage of rice seeds (from seed production cropping), and will allow farmers to obtain higher prices in markets.

- Harvesting: Harvest rice at the correct stage of maturity, i.e. when 80–85% of the panicles are straw colored and grains at the lower part of the panicles are hard and brittle to the bite. Most subsistence farmers clip the rice panicles with a knife (Fig. 14a) and collect them in a sack for drying near the house. Other farmers use sickles to harvest the rice crop at a convenient height (Fig. 4.14b). Some farmers may also use reapers or brush cutters to harvest rice.
- Threshing: Thresh the rice crop immediately after harvest to minimise grain damage by insects, birds, rodents, mold and attack by other seed pathogenic fungi. Manual threshing is common in countries like Cambodia, Laos and Myanmar. Farmers are encouraged to use portable threshers which will thresh and clean the grains at the same time.
- Cleaning: Clean manually threshed grains by repeated winnowing to remove chaff (unfilled grains) and other impurities.
- Drying: Dry the rice grains immediately after threshing and cleaning . This means reducing the moisture content to 14% for food grains and 12–13% for grains to be used for seeds. Delays in drying will cause quality deterioration (grain discoloration) and also physical losses. An immediate drying will preserve milling, cooking, odor, and eating quality of the milled rice. Dry the grains on a hard floor or on mats in open sunlight, or under ventilated plastic domes. Stir the grains at regular intervals so that the grains dry slowly and uniformly. Optimum temperature for drying will be < 60–65 ºC for food grains and < 43–45 ºC for grains to be used as seeds.

- Grains that are clean and dry store better and improve both the milling output and quality of the milled rice. Likewise, rice seed cleaning and drying will improve seed quality, storability, and increase crop yields when the seeds are planted in the following season.
- Grain storage: Improved grain storage at the farm level is critical for storing both grains and seeds for future use. Grains can be stored either in traditional woven plastic and burlap gunny sacks, or in sealed airtight storage containers. Air tight storage structures or containers prevent grains from re absorbing moisture from the surrounding air and/or rain, as well as reducing grain damage by pests during storage. Air tight (hermitic) storage is preferred for storing seeds for planting in the following season.
- Milling: Milling is the final step in the post-production management of paddy. Rice milling efficiency depends on the entire post-harvest process from harvestig at the right crop maturity to drying and cleaning as described above. Millers prefer clean, dry (14% moisture content [MC]) paddy of a good quality for milling. The output of milled rice and its quality are highly affected by the milling process and the type of equipment used. Hand pounding of paddy is still practiced in some remote villages of Laos, Cambodia, Myanmar, Indonesia and Philippines. Three types of rice mill are used in Asia: (a) steel huller (Engelberg type); (b) under run disc sheller; and (c) rubber roller system as in modern rice mills. The first two types of mill are common in Asian villages and they operate using two stages: (i) removing husks from the paddy; and (ii) removing bran from the brown rice. The rural mills are well maintained and skillfully operated in order to get a high output of good quality milled rice.

Modern commercial mills have pre-cleaners and separators to clean and grade the paddy, rubber rollers to remove the husks and separate the brown rice from husks. Two separate whiteners and one polisher are used to remove the bran and polish the rice, and an electronic grader is used to grade the polished white rice grains.

The millng efficiency is indicated by the total output of milled rice (whole grains + brokens), per cent of milled whole grains (head rice), and overall quality of milled rice. The milling efficiency of different systems is shown earlier in Table 3.3.

(a) (b)

FIG. 4.14. Two types of harvesting upland rice: (a) clipping the panicles with a knife and (b) harvesting the crop with sickles [6].

4.7. ADAPTATION TO CLIMATE CHANGE IN ASIAN UPLANDS

Most of the Asian upland farmers are already impacted by declining rice yields due to rising deforestation in upper watersheds, increased soil erosion, depletion of organic matter and nutrients, weeds infestation, and poor soil moisture retention capacity. Small holders and subsistence farmers are the most vulnerable to the adverse impacts of continued deforestation and changing climate – loss of biodiversity, unreliable rainfall, rising temperature, and increasing occurrence of droughts and other natural calamities. The isolated location of villages and families as well as their inaccessible mountainous terrain make is difficult to provide emergency disaster relief to people and to deliver critical inputs and technical support to farmers; as a consequence, people living in such remote areas suffer from extreme poverty and malnutrition. How can we make them climate resilient?

Foremost, in deforested upper watershed areas, best practices such as improving vegetation cover, reducing soil erosion and reviving local headwater streams may help to stabilise the water flow to downstream areas.

In farming areas, improving crop and grazing land management practices is critical; farmers can restore organic matter in soils and construct contour hedges or live barriers to reduce soil erosion and to enhance infiltration of rainwater into the soil. More organic matter also means better soil quality, higher water holding capacity, and higher crop yields, all combined with an increased nutrient use efficiency. Farmers can also change the planting dates to suit changing rainfall patterns and or shortening crop growing seasons.

Educating (training) several local leaders in every village as 'climate risk managers' could be a useful strategy. These leaders could then help the rest of the community in implementing early disaster warning systems and implementing adaptive measures for droughts, floods and cyclones, as well as for good, stable weather predictions.

Additional details on improving upland agroecosystems and people's livelihoods are provided in the next section.

4.8. RESTORING SUSTAINABLE LANDSCAPES AND LIVELIHOODS IN ASIAN UPLANDS

In mountainous uplands, restoration and management of landscapes and maintenance of common resources and services are important for cultivation of upland rice and other crops and raising farm animals in a sustainable manner. Farmers living in such areas may need to diversify into the production of high value cash crops, tree crops and non-timber forest products (NTFPs), e.g. the rearing of livestock, the development of fishing, and the cultivation of river gardens [6]. The extent of farmer adoption of diversification strategies will depend on the availability of suitable crop species, the availability of labour and the requirement of other facilities including markets to develop new, diverse crops. Here, the need for external inputs is considered and evaluated. This includes increasing the use of farm machines, fertilisers and other chemicals and the need for veterinary support. The level of initial investment, and the returns and risks associated with new enterprises are carefully evaluated. Additionally, the impact of new enterprises on the environment and on natural biodiversity is assessed. Other factors which can determine the farmers' choice of options include (a) whether their land is located near, or far away from roads, (b) market access and demand for new products, and (c) whether the farmer has access to montane paddy fields.

4.8.1. Exploitation of natural and agro-biodiversity

Farmers currently live on rice as a staple food, but they also often consume a large number of aquatic and terrestrial animals and plants, organisms which form the natural and agro-biodiversity of the landscape, from mountain tops to valley bottoms [23]. Most of the herbal medicines and non-timber products are collected from forests and crop lands in fallow, and these products are used either for home consumption or sold in local markets. While rice is the most valuable domesticated species from the natural biodiversity; other valuable species include bamboo, rattan, paper mulberry, broom grass, job's tear, medicinal and essential oil plants, etc. Proper exploitation and careful management of both the natural and agro-biodiversity is crucial for maintaining the integrity of both natural ecosystems and cultivated agroecosystems – both of these landscapes are vital for human welfare and survival.

4.8.2. Agricultural diversification

The type of uplands and the ease of access to uplands determine the kind of diversification of uplands for enhanced productivity and profitability as shown below.

High potential, favorable uplands located on gentle slopes just above the valley bottoms:

Continuous upland rice cropping, accomplished in rotation with planted fallows or other crops (sesame, peanut, or soybean) is feasible here. With adequate inputs, rice yields can be as high as 3 to 4 t ha^{-1}.

a. Unfavorable uplands on slopes greater than 30% with medium to poor fertility soils:
    - Plant alternative crops like job's tear, sesame, peanut, or pigeon pea, either as pure or mixed species crops.
    - Entomo forestry (growing crops and raising insects together): Farmers can plant pigeon pea and develop stick lac (a resin produced by an insect species living on pigeon pea plants) wherever possible.
    - In drought prone uplands, farmers can replace upland rice with cassava, which can be sold to the cassava powder industry. Or the land can be used for communal grazing of livestock.

b. Uplands located near roads (or streams):
    - Plant commercial crops (Fig. 4.15) that have a high market demand, i.e. crops like pineapple, banana, papaya, vegetables, fruits, etc.

(a)

(b)

(c)

FIG. 4.15. Commercial crops (a) banana, (b) pineapple, (c) onion) cultivation on suitable uplands with access to good roads, transport and markets, Northern Laos [6].

Remote uplands with no access to roads and markets:

Farmers are allowed to continue the slash and burn method of upland rice based farming with long fallow periods (15 years or more between 1–2 years of cropping); hunting and gathering and selling of non-timber forest products are other livelihood options. Food insecurity and malnutrition will, however, likely remain high in these areas.

4.8.3. Integrated crop-animal systems

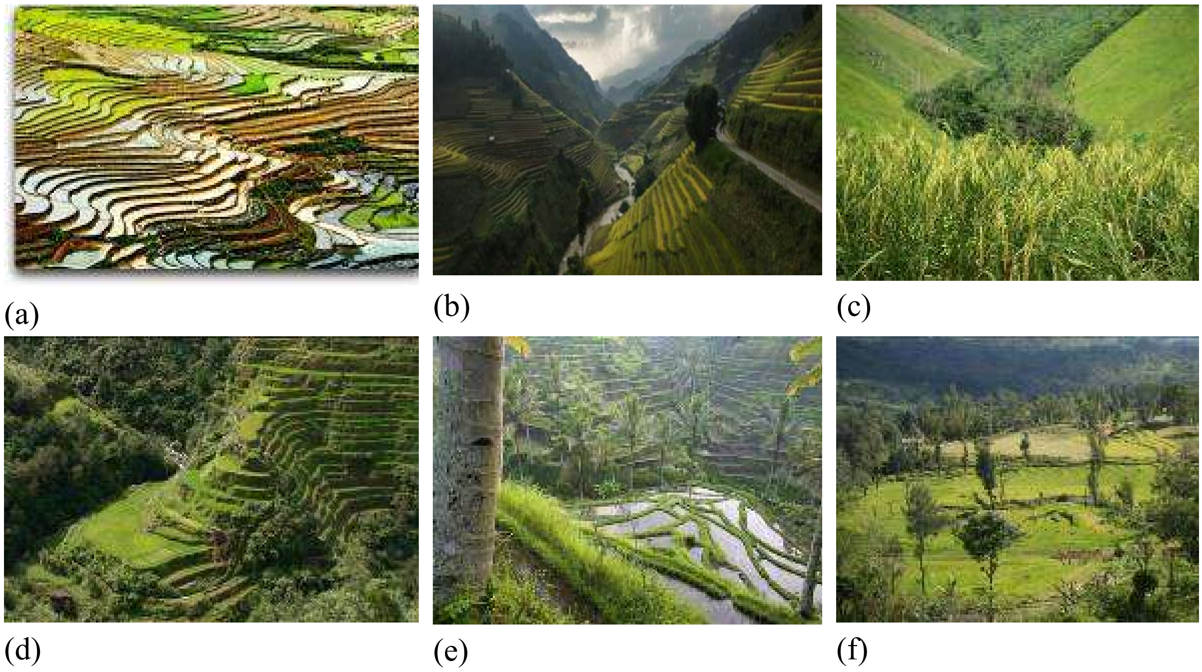
When properly integrated and well managed, crops and livestock can be highly complementary to each other. Crop residues and by-products are fed to animals and vegetation from fallow lands will be available for grazing by animals. Animal manure can be added to crop fields to improve soil fertility. Livestock, small animals and poultry can play an important role, both as a source of cash income and as food, especially for the poor. Introduction and evaluation of new domestic animal species, such as rabbit or turkey, could broaden the farmers' choice of livestock which are best adapted to their conditions. Access to better breeds and vaccination to prevent diseases (bird flu in chickens, or blue ear syndrome in pigs) is important to improve livestock production. Development of fodder crops and a cut and carry fodder system to feed the animals will help intensify the livestock production systems. This will also prevent crop damage by free range animals in the summer season, when some farmers with the ability to irrigate can plant crops.

4.8.4. Fish farming and collecting aquatic organisms and plants

Farmers living near rivers currently use fishing and the collecting of natural aquatic organisms (snails, crabs, etc.), and plants (various greens and vegetables) in river gardens to diversify their food and income sources. Improved fish breeds, locally adapted improved methods for fish feeding, and strategies and methods to prevent depletion of natural fish stocks in rivers, are critical for maintaining a sustainable fish farming 'industry'.

4.8.5. Agro-ecotourism

Finally, the potential of agro-ecotourism as a method to alleviate poverty in selected remote areas of Asian uplands can be explored. Some of the rice landscapes on the rolling hills and steeply sloping mountains of south and south east Asian countries are amazingly beautiful (Fig. 4.16), at least during the rainy season (e.g. northern Laos, terraced rice fields of Guangxi and Ha Jiang in People's Republic of China, Bali and Java uplands in Indonesia, north eastern states of India, the Ifugao rice terraces in the Philippines, and the terraced hills of Myanmar, Nepal and Thailand). Development of sustainable agro-ecotourism in these selected areas may open up new income generating opportunities for local communities in both of hospitality services and small trade. The National Tourism Development Authorities such as they can evaluate the potential of this venture and look for funding from various sources to develop it to its full potential.



(a) (b) (c) (d) (e) (f)

FIG. 4.16. Beautiful rice landscapes in Asian uplands: (a) Terraced rice fields, Ha Jiang, People's Republic of China; (b) Rice fields on terraces, Thailand (Photo by Jakkree Thampitakkul); (c) Rice landscapes on rolling hills in northern Laos (Photo by V. Balasubramanian); (d) The 2000 year old Banaue rice terraces, Ifugao, Philippines; (e) Terraced rice fields in Bali, Indonesia; and (f) Rice terraces in Builale, Baucau, Timor Leste [6].

4.9. REFERENCES CHAPTER 4

[1] GLOBAL RICE SCIENCE PATNERSHIP (GRISP), Rice Almanac, 4th Edition, International Rice Research Institute (IRRI), Los Banos, Philippines (2013) 283 pp. irri.org/resources/publications/books/rice-almanac-4th-edition

[2] IRRI, Major Research in upland rice, International Rice Research Institute (IRRI), Los Baňos, Philippines, (1975).

[3] BALASUBRAMANIAN, V., et al., Increasing rice production in sub-Saharan Africa, Challenges and opportunities, Adv. Agron. **94** (2007) 55–133.

[4] HASEGAWA, S., Upland rice (in Japanese), In: Togari Y (Eds) Crop Science, a Treatise, The Rice Plant Yokendo, Tokyo, **1** (1963) 1–124.

[5] TUNG, T.C., Soils of the ASPAC region, Part 7, South Viet Nam, ASPAC, Food Fertilizer Technical Center, Technical Bulletin, **16** (1973) 29 pp.

[6] BALASUBRAMANIAN, V. A., Vision for Lao uplands, A comprehensive report prepared for National Agriculture and Forestry Research Institute (NAFRI) and submitted to the Swiss Agency for Development and Cooperation (SDC), Vientiane, Lao PDR, NAFRI and SDC; Los Baňos, Philippines, International Rice Research Institute (2008) 52 pp.

[7] RODER, W., Slash-and-Burn Rice Systems in the hills of Northern Lao PDR, Description, challenges and opportunities, International Rice Research Institute, Los Baňos, Philippines (2001).

[8] BECKER, M., JOHNSON, D.E., Cropping intensity effects on dryland rice yield and sustainability in West Africa. Nutr. Cycl. Agroecos. 59 (2001) 107–117.

[9] AKANVOU, R., et al., Effects of sowing dates on cover legumes-dryland rice intercropping systems in West Africa, Biolog. Fert. Soil. **33** (2001) 15–21.

[10] IRRI, Progress in upland rice research, Jakarta Conference, International Rice Research Institute (IRRI), Los Baňos, Philippines (1986).

[11] RODER, W., MANIPHONE, S., KEOBOULAPHA, B., Pigeon pea for fallow improvement in slash-and-burn systems in the hills of Laos, Agrofor. System. **39** (1997) 45–57.

[12] COYNE, D.L., SAHRAWAT, K.L., PLOWRIGHT, R.A., The influence of mineral fertilizer application and plant nutrition on plant-parasitic nematodes in dryland and wetland rice in Côte d'Ivoire and its implications in long-term agricultural research trials, J. Exp. Agric. **40** (2004) 245–256.

[13] PLOWRIGHT, R.A., HUNT, D.J., Plant parasitic nematodes of dryland, hydromorphic and inland swamp rice ecosystems in Côte d'Ivoire, Afro-Asian J. Nemat. **4** (1994) 61–67.

[14] ONO, S., Upland rice breeding in Japan, JARQ **6** (1971) 68–72.

[15] HILL, B., A mountainous success, Rice Today (IRRI), (2006).

[16] HAEFELE, S.M., BOUMAN, B.A.M., Drought-prone rain-fed lowland rice in Asia: Limitations and management options. In: Drought frontiers in rice, (2009) 211–232.

[17] AKANVOU, R., et al., Fallow residue management effects on dryland rice in three agro-ecological zones of West Africa, Biol. Fert. Soil. **31** (2001) 501–507.

[18] DOBERMANN, A., WITT, C., DAWE, D., Increasing the productivity of intensive rice systems through site-specific nutrient management. Enfield, N.H. (USA) and Los Baños (Philippines), Science Publishers, Inc., and IRRI (2004) 410 pp.

[19] WITT, C., et al., Principles and promotion of site-specific nutrient management, 397–410. In: A. Doberman, C. Witt and D. Dawe (ed.), Increasing productivity of intensive rice systems through site-specific nutrient management, Enfield, NH, USA, International Rice Research Institute, Science Publishers Inc. and Los Baños, Philippines (2004).

[20] RODER, W., PHENGCHANH, S., KEOBOULAPHA, B., Relationships between soils, fallow periods, weeds and rice yield in slash-and-burn systems of Laos, Plant & Soil **176** (1995) 27–36.

[21] JOHNSON, D.E., et al., The influence of rice plant type on the effect of weed competition on Oryza sativa and Oryza glaberrima, Weed Res. **38** (1998) 207–216.

[22] CARSKY, R.J., BECKER, M., HAUSER, S., Mucuna cover crop fallow systems, Potential and limitations, In ‘Sustaining Soil Fertility in West Africa’, SSSA Special Publication No. 58 (R. J. Carsky et al., Eds.), Soil Science Society of America, Wisconsin, USA **58** (2001) 111–135.

[23] BALASUBRAMANIAN, et al., Enhancing Agro-biodiversity in Lao Uplands, Identifying and Utilizing Niche Habitats in Farm, A report submitted to Swiss Agency for Development and Cooperation (SDC), Vientiane, Lao PDR (2008) 52.

5. PROTOCOLS FOR ^{15}N MICROPLOT TECHNIQUES FOR ESTIMATING FERTILISER NTROGEN USE EFFICINCY IN FLOODED RICE SYSTEMS

5.1. ROLE OF N IN PLANTS

Nitrogen (N) is an essential plant nutrient being a component of amino acids, nucleic acids, nucleotides, chlorophyll, enzymes, and hormones. N promotes rapid plant growth and improves grain yield and grain quality through higher tillering, leaf area development, grain formation, grain filling, and protein synthesis. N is highly mobile within the plant and soil.

5.2. WHY TO APPLY N FERTILISERS TO CROPS

Nitrogen is the most limiting element in almost all soils. Thus, proper application of N fertilisers is vital to improve crop growth and grain yields, especially in intensive rice production systems. Balancing N application with other nutrients (P, K, S, Zn, etc.) is important for efficient N use by plants. In flooded rice systems of Asia, farmers apply mostly urea (46% N), followed by di ammonium phosphate (18% N and 19–20% P). Only in saline alkaline soils, farmer use some amount of ammonium sulphate (21% N, 24% S). Optimal N management strategies aim at maximizing crop N uptake and minimizing N losses to the environment.

5.3. FATE OF APPLIED N IN FLOODED RICE SYSTEMS

Under flooded conditions, both water and N application methods affect the transformation and movement of applied N in crop fields. With increasing water scarcity, Asian farmers are moving from continuous flooding (CF) to alternate wetting and drying (AWD) irrigation. In AWD irrigation, the soil experiences aerobic conditions during the drying phase and anaerobic conditions when flooded [1]. The level of O_2 in soil plant water system will determine the extent of nitrification (in aerated soil) and denitrification (in flooded soil) of applied N. The pH and temperature of the floodwater will influence ammonia volatilisation in rice fields. Soil microbes play a crucial role in N transformations: (a) under aerobic conditions, immobilisation of mineral N into organic N and mineralisation of organic matter to release mineral N, and (b) under flooded (anaerobic) conditions, denitrification of nitrate-N into oxides of N and inert N_2 gas that escape into the atmosphere. Here the nitrous oxide (N_2O) evolved from soils is a potent greenhouse gas (GHG) that influences climate change.

Overall, N applied to flooded rice fields is either taken up by crops; remain in the soil as mineral N or as immobilised organic-N, or lost from the soil plant water system. N losses from rice fields can be through leaching of mineral N (NH_4-N and NO_3-N) into the groundwater, surface runoff of soluble N (NH_4-N and NO_3-N) from farms to the environment, volatilisation of ammonia (NH_3) into the atmosphere, and gaseous N losses (oxides of N and or inert N_2 gas) due to denitrification. Thus, insufficient and/or inappropriate fertiliser N management can be equally detrimental to both crops and the environment, particularly the pollution of water and air. Both lack of N (N deficiency) in or excess N uptake by plants will adversely affect plant growth, make the plants susceptible to pests and diseases, and reduce grain yields drastically. Increased pesticide application to control pests on over N fertilised crops and N_2O evolved from soil contribute to environmental pollution and climate change that affect people within and beyond farms. Therefore, farmers' N management strategies aim at increasing fertiliser N use efficiency (fertiliser N uptake) by crops and reducing N losses to the environment.

5.4. ^{15}N TECHNIQUES TO TRACE THE FATE OF APPLIED N IN FLOODED RICE SYSTEMS

Various analytical methods are available to determine the fate of applied N in cropping systems. One of the methods used for tracing the route of applied N is the N tracer techniques that allow quantitative assessment of fertiliser N use efficiency (FNUE) by crops; N transformation processes in soils; crop uptake of the ^{15}N-labelled fertiliser N vs. N taken up from soil derived mineralised organic N and residual mineral N sources; N recycled from crop residues and or previous green manure/cover crops; and the fate and transport of ^{15}N-labelled fertiliser N. The term '^{15}N-labelled fertiliser' denotes either ^{15}N-enriched or ^{15}N-depleted fertilisers [2].

5.4.1. Fertiliser ^{15}N materials

Enriched ^{15}N materials are expensive, thus only small amounts of ^{15}N are applied in field experiments. ^{15}N-labelled fertilisers are available either in ammonia (NH_3), ammonium (NH_4^+), nitrate (NO_3^-), and urea [$CO(NH_2)_2$] forms. The ^{15}N enrichment levels commonly available are 2, 5, 10, 60 and about 99 atom%.

5.4.2. Field experiments with ^{15}N-labelled fertilisers

Field experiments using ^{15}N-labelled N fertilisers vary from those with single plants to lysimeters to micro plots. Studies with ^{15}N-labelled fertilisers are ideally conducted under conditions that represent farmers' soil and crop management practices as much as possible. There are two general types of experiments: (a) micro plots with no physical barriers around that are often used for crops under non-flooded conditions and (b) those with physical barriers around that are used for flooded rice systems. Both types require the use of ^{15}N-labelled materials and access to the isotopic analysis laboratory.

5.4.3. Details of protocols for ^{15}N-urea fertiliser experiment in direct seeded flooded rice systems

Certain protocols need to be followed to reduce potential cross contamination problems and to allow the collection of high quality data for interpretation and analysis of experimental results. The protocols described here have been distilled from that the published article of [3]. It involves the micro plots with physical barriers around to prevent the lateral movement of applied ^{15}N-labelled fertiliser N through water or soil from micro plots to larger experimental plots and vice versa. The size of micro plots is large enough to contain sufficient volume of soil for normal development of roots of experimental rice plants. The protocols are robust enough to monitor the N in plant and soil and determine all N losses to the environment.

5.4.3.1. Soil type and site description

- Describe the location of the experimental site with the help of a Google map.
- Provide data on the characteristics of the surface (0–15 cm) soil: soil type; % of sand, silt and clay; bulk density; % of soil organic C and total N, and C:N ratio; electrical conductivity; available P, K, S and Zn.

5.4.3.2. Field experimental details

- Experimental design: Split plot with 2 irrigation regimes as main plot treatments x 5 sampling times as sub plot treatments, replicated 4 times.
- Demarcate 8 experimental field plots of size 5 m x 4 m and allocate 4 plots for continuous flooding (CF) and 4 for AWD. Each plot will have a buffer channel all around to minimise lateral water movement and will receive irrigation water directly from the field irrigation channel (Fig. 5.1).

FIG. 5.1. Experimental field plots with buffer all around and the field channel for irrigating individual plots as and when necessary (at will) (Photo of irrigation experimental plots, Aduthurai, Tamil Nadu, India) [4].

- Prepare and level the soil in each plot and apply the P fertiliser at 14 to 18 kg P ha^{-1} and the first dose of K fertiliser at 25 kg K ha^{-1}, one day before sowing. Apply the 2nd dose of K fertiliser at 8–10 kg K ha^{-1} at active tillering (45 days after seeding, DAS).

- Apply urea-N fertiliser at 90 kg N ha^{-1} in three equal splits (30 kg N ha^{-1} for each split) at 12, 22, and 44 DAS.

- Use the seed rate of 80 to 100 kg ha^{-1}, soak and pre-germinate the required quantity of seeds, and sow the seeds in rows 20 cm apart in each plot.

- Apply the post-emergence herbicide a few DAS, and the required fungicides and pesticides as per the need at locally recommended rates.

- For the first 3 DAS, drain all the plots to enhance seedling emergence and root development and anchorage into the soil. From 3 to 10 DAS, keep the water level at 1–2 cm above soil surface in all 8 plots (both water management treatments).

- Impose the two irrigation treatments at 10 DAS.

- For the 4 CF plots, irrigate regularly to maintain a water level of 5 ± 2 cm above soil surface until physiological maturity of the rice crop (~90 DAS) and then drain the plots and allow the soil to dry out until 7 days after harvest when the final soil samples are taken.

- In the 4 AWD treatment plots, irrigate to a water level of 5 ± 2 cm above soil surface, and allow the water level to drop to 10–15 cm below the soil surface (to a drained soil moisture equivalent to 60% of water holding capacity) before next irrigation is given. Maintain this cycle of wetting and drying throughout the vegetative phase of the crop (10 to 60 DAS). From panicle initiation to physiological maturity of the crop (60 to 90 DAS), irrigate regularly to maintain a water level of 5 ± 2 cm above soil surface and then drain the plots and allow the soil to dry out until 7 days after harvest when the final soil samples are taken. Make the topdressing of N and K fertilisers to coincide with irrigation events for the AWD plots.

5.4.3.3. Establishing and managing micro plots

The N budget or balance for each of the eight experimental plots is investigated by following the fate of ^{15}N-enriched urea fertiliser applied in micro plots.

- Establish one micro plot in each of the 8 experimental plots (4 for CF and 4 for AWD) on the day before the first application of ^{15}N-enriched urea. This is done by inserting a plastic frame (50 cm x 50 cm, 30 cm high) into the hard subsoil layer to a depth of 20 cm at the chosen place in each of the field experimental plots in such a way that 10 cm of the frame remains above the soil surface. Keep the frames in place until after the last soil sampling 9 days after the harvest of the rice crop.

- There will be three 50 cm long rows of rice in each micro plot.

- Prepare ^{15}N-labelled urea of 47.8% ^{15}N by mixing ^{15}N-urea (99.1% atom excess ^{15}N, Sigma-Aldrich) with unlabelled urea.

- Calculate the amount of ^{15}N-labelled urea for each micro plot for an N rate of 30 kg N ha^{-1} and dissolve it in deionised water. Mix this ^{15}N-labelled urea solution into the floodwater in each of the micro plots. Simultaneously apply uniformly the first dose of unlabelled urea (at 30 kg N ha^{-1}) outside the micro plot area in each of the experimental plots.

- Apply the 2nd and 3rd dose of N (at 30 kg N ha^{-1}) on predetermined dates by mixing ^{15}N-labelled urea solution into the flood water in micro plots and unlabelled urea outside the micro plots.
- Make sure that water management and K topdressing is identical inside and outside the micro plots.

5.4.3.4. Soil sampling and analysis

This section describes the stepwise method for collection of composite soil samples for chemical analyses. These include:

- Use a steel auger (of 2 cm inner diameter) to take 5 cm deep soil cores between the rice rows in each of the micro plots at pre-determined dates: (a) prior to basal fertilisation (one day before sowing); (b) 15 DAS (3 days after first ^{15}N-labelled urea topdressing); (c) 65 DAS (right after panicle initiation); (d) 100 DAS (right after rice harvest); and (e) 107 DAS (one week after rice harvest). For each soil sampling, take 4 cores from each micro plot and mix them to form the composite sample for extraction and analysis.
- Transfer the soil samples immediately to insulated plastic containers at 6ºC and transport the samples to the laboratory on the same day of sampling.
- In the laboratory, remove the visible roots and process the soil samples on the next day of sampling.
- Measure soil pH by a pH electrode in pore water obtained from 20 ml of wet soil by centrifugation (at 3000 rpm for 10 minutes at room temperature) and subsequent filtering (cellulose acetate, 0.45 µm).
- KCl Extract of soil samples: Mix 4.5 ml of wet soil sample with 2M KCl (1:10 ratio, vol/vol) in a 50ml centrifuge tube. Shake horizontally the centrifuge tubes containing soil KCl mixture for 65 ± 5 minutes and centrifuge immediately (at 3000 rpm for 10 minutes at room temperature). Filter (cellulose acetate, 0.45 µm) the supernatant and freeze (−20 ºC) the filtrate for later analysis.
- Determine the inorganic N contents in KCl extracts by a standard spectrophotometric procedure for ammonium [5] and by the cadmium reduction method for nitrate plus nitrite [6].
- Determine the NH_4^+ in KCl extract by converting it to N_2 gas with hypobromite [7], and then measure ^{15}N-N_2 by mass spectrometry.
- Transfer the remaining soil slurry from each 50 ml centrifuge tube after KCl extraction to an aluminium dish, over dry it for 72 hrs at 70 ºC, and store it in 15 ml sterilised tube for later analysis of total ^{14}N and ^{15}N contents on a C:N analyser (Robo Prep C:N, Europa

Scientific, UK) in line with an isotope ratio mass spectrometer (Robo Prep G+ in line with Tracer Mass, Europa Scientific, UK).

5.4.3.5. Laboratory Incubation Experiments

This section describes the stepwise method for setting up an incubation experiment to measure potential mineralisation and nitrification. These include:

- Quantify the potential nitrification activity (an estimate of nitrifier population size in the soil) by aerobic incubation of NH_4-enriched soil slurries (n = 2 for each micro plot) as the rate of nitrate plus nitrite production [8]. Add 3 g of wet homogenised soil to 50 ml sterile centrifuge tubes containing 40 ml of air saturated deionised water, 2.0 ml of 4 mM KH_2PO_4, and 1.0 ml of 20 mM NH_4Cl. Mix vigorously the contents in each tube and then incubate for 24 hrs on a rotating shaker at room temperature. Remove 5 sub samples (each 9 ml of slurry) for nitrite analysis from each tube at fixed intervals during the 24 h incubation period, centrifuge for 10 minutes at 3600 rpm, filter (GF/C filter, Whatman), and freeze (at −20ºC) for later analysis of nitrite as described above.
- Measure the net N mineralisation in anoxic soil slurries as the change in NH_4^+ concentration over time. Prepare a soil slurry in a 500 ml glass bottle by mixing 40 ml of wet soil with 160 ml of anoxic deionised water (gassed with N_2 for 30 min). Cap the bottles and exchange the head space with pure N_2 and shake vigorously for 2 min. Repeat the procedure once again to remove O_2 from the slurry. Subsequently, use a 20 ml plastic syringe with attached tubing to transfer the slurry to 1.6 ml glass vials (Exetainer, Labco High Wycombe, UK) and fill them completely with the slurry and cap them without any air bubbles. Then incubate the Exetainer vials on a rotating shaker at room temperature for up to 7 days. Harvest duplicate vials each day of incubation from each experiment for KCl extraction and analysis of NH_4^+ content as described above.

5.4.4. In situ Gas Flux Measurement

A modified closed chamber method (Fig. 5.2) can be used to measure the evolved $^{15}N_2$ gas from micro plots within 4 h after each application of ^{15}N-labelled urea.

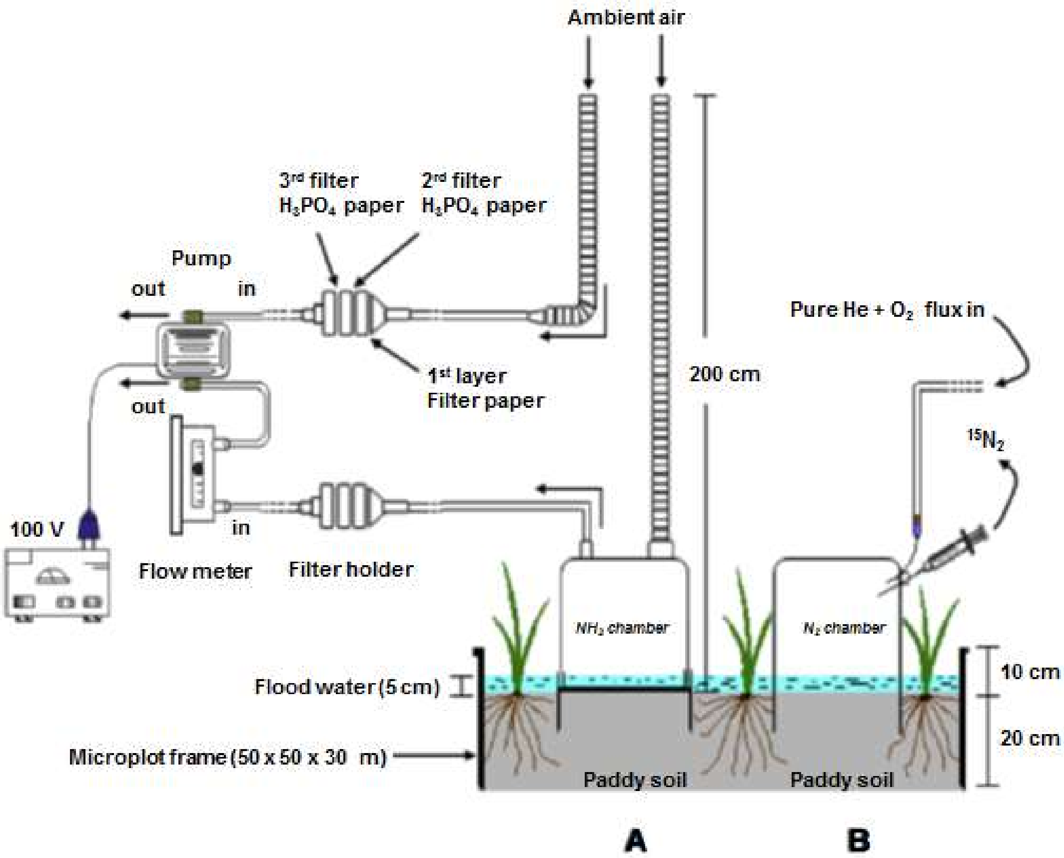


FIG. 5.2. Schematic diagram of the modified dynamic chamber for ammonia volatilisation measurement (A) and the direct sampling method N_2 emission measurement (B) under field conditions. The chambers cover an area of 10 cm x 10 cm, and are pushed into the soil to leave a 20-cm high gas space inside, giving a chamber volume of approximately 2 L [2].

- Inside each micro plot, one transparent rectangular chamber (10 cm x 10 cm x 30 cm) is pushed into the soil to a depth of 5–10 cm, leaving 2 L of head space above soil water surface (Fig. 5.2). An opening at the top prevents the build-up of pressure inside the chamber while it is inserted into the soil. After insertion, the opening is closed with a rubber stopper that acts as a gas sampling port.

- Initially, the air inside the chambers is flushed with a mixture of 80% He and 20% O_2 for at least 15 min. to reduce the concentration of N_2 and increase the sensitivity of the $^{15}N_2$ gas analysis.

- A total of 6 gas samples (4 ml each) is taken over a period of 72 hrs. Initiate the N_2 gas flux experiment in the afternoon on day 1 and take the first gas sample about 2 hrs after the start of the experiment. Take the remaining 5 samples in the morning and afternoon of day 2 and day 3, and finally in the afternoon of day 4. Collect the gas samples in duplicate for each time point with a 5 ml plastic syringe with a hypodermic needle from the sampling port and inject it into a 6.6 ml glass vials (Exetainer, Labco High Wycombe, UK) prefilled with He-purged deionised water; the deionised water is drained out through an inserted hypodermic needle as the 4 ml gas sample is injected.

- Determine the amounts of $29N_2$ and $30N_2$ as µmol in each sample, using an isotope ratio mass spectrometer (Robo Prep G+ in line with Tracer Mass; Europa Scientific, Crewe, UK); then calculate and express the results as excess above their natural abundances.
- Calculate the production rates of $29N_2$ and $30N_2$ per unit time as slopes of the linear regression lines of amounts of labelled $29N_2$ and $30N_2$ vs. time. Then, calculate the production rates of $29N_2$ and $30N_2$ per unit area per unit time (µmol per m^2 per h) as the $29N_2$ and $30N_2$ per unit time (µmol per h) divided by the soil water surface area (m^2) within the N_2 flux chamber. Assuming random isotope pairing, these rates are used to estimate ^{15}N and ^{14}N gas production according to the following equations [9]:

$$D15 = p29N_2 + 2\,x\,p30N_2 \tag{1}$$

$$D14 = (D15\,x\,p29N_2) / (2\,x\,p30N_2) \tag{2}$$

$$Df = D15 / F \tag{3}$$

Where

D15 and D14 are denitrification rates of ^{15}N and ^{14}N;

Df is the total denitrification of fertiliser N;

F is the fraction of ^{15}N-urea / total urea-N (= 0.478)

$p29N_2$ and $p30N_2$ are production rates of $29N_2$ and $30N_2$, respectively.

Total N loss over the growing season is calculated according to Eq. (4).

$$Total\ N\ loss = R_1\,x\,PL_1 + R_2\,x\,PL_2 + \cdots \ldots \ldots Rn\,x\,PLn \tag{4}$$

Where

*R*n is the N_2 emission rate on day n and PLn is the length of period n.

- Period length is calculated as the number of days from the midpoint between sampling dates n and n1 and the midpoint between sampling dates n and n+1. The first period starts at the day of the first topdressing of urea and the last period is set to end at 107 DAS (the day of last soil sampling).
- Measurement of ammonia volatilisation: The dynamic chamber method is used to measure ammonia volatilisation immediately after each ^{15}N-labelled urea application and repeated measurements are taken at least 4 times (0, 2, 4 and 6 days after fertilisation).

- Place the ammonia collection chambers (10 cm x 10 cm x 20 cm = volume 2 L) over the stainless-steel bases inserted into the soil between rice rows with no plants enclosed. Adjust the steel bases in such a way that the 2 L volume is obtained above the soil water surface.
- Generate airflow by a 4 gates pump with a ventilation rate of > 15 L per min. for the chamber line and > 20 L per min. for the ambient air line. The air from each line passes through a filter holder with three filters in line: the first 0.8 µm pore size polytetrafluoroethylene (PTFE) filter removes the dust and particulates from the passing air, while the subsequent two 47 mm cellulose filters wetted with phosphoric acid (H_3PO_4) trap the ammonia in the gas stream.
- Simultaneously, monitor the temperature and pH of the floodwater at each plot by using an electronic thermometer and a portable pH electrode.
- The frequency of measurement is twice per day with 2 hrs of continuous pumping from 9 to 11 am and from 2 to 4 pm.
- After each measurement, keep the filter holders in a cool box and take them to the laboratory for analysis.
- In the laboratory, extract the trapped ammonia with 10 ml of deionised water and measure the ammonia concentration calorimetrically.
- Calculate the ammonia volatilisation flux rate as follows [10]:

$$Fa = [(Cch - Camb)\ x\ V]\ /\ (t\ x\ S) \tag{5}$$

Where:

*F*a is the flux rate of ammonia;

*C*ch and *C*amb are the concentrations (µmol per m^3) of ammonia in the chamber air and ambient air, respectively;

V is the air flow rate (m3);

t is the incubation time (h); and

S is the surface area (m^2) of the soil water surface inside the chamber.

The daily ammonia flux rate is estimated by assuming that the night time (12 h) flux is equal to half the day time flux [11].

Total ammonia volatilisation over the crop growth season is estimated as for the N_2 emission above [Eq. (4)].

5.4.4.1. *Sampling and Analysis of Plant Materials*

At harvest, collect all the rice plants within each chamber and record the fresh weights for roots, straw, and grains separately. Sample roots to a depth of 15 cm within the rice rows by using a steel tube (5 cm diameter) and wash the collected roots with distilled water to remove the soil particles. Oven dry the plant samples at 70 ºC to constant weight, grind the dried materials by a hammer mill (mesh size 0.1 cm), and store the powdered samples in sterilised plastic bags for later analysis of total N and ^{15}N content by using the same process as for soil samples. Calculate the plant agronomic indices as follows:

$$Nf\ (\%) = \frac{(\%\ atom\ excess\ of\ 15N\ in\ plant)}{(\%\ atom\ excess\ of\ 15N\ in\ urea)}\ x\ 100 \tag{6}$$

$$Nf = N\ uptake\ x\ Nf\ (\%) \tag{7}$$

$$Ns = N\ uptake - Nf \tag{8}$$

$$(FNUE\ \%) = Nf\ /\ N\ fertiliser\ x\ 100\% \tag{9}$$

$$NHI = N - grain\ /\ N\ uptake \tag{10}$$

$$HI = DW - grain\ /\ TDW\ aboveground\ biomass \tag{11}$$

Where:

Nf is plant N derived from the applied fertiliser;

Ns is plant N not derived from the applied fertiliser;

N uptake is total plant N uptake;

N-grain is total N in grain;

FNUE = Fertiliser N use efficiency;

N fertiliser is the total amount of fertiliser N added to the soil;

NHI is the N harvest index;

HI is the harvest index;

DW grain is the dry yield of grain; and

TDW aboveground biomass is the total dry weight of aboveground biomass.

5.5. STATISTICAL ANALYSIS

The data for NH_4^+ and NO_x^- (nitrate and nitrite) contents, net N mineralisation rates, and potential nitrification rates are assessed by two-way ANOVA using any suitable statistical software to see the effect of two water regimes and sampling time on the difference of mean values and also to test for significant interactions of water regimes x sampling time.

5.6. . REFERENCES CHAPTER 5

[1] DONG, N.M., et al., Effects of alternate wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Viet Nam. Soil Biol. Biochem. **47** (2012) 166–174.

[2] FOLLET, R.F., Innovative ^{15}N micro-plot research techniques to study nitrogen use efficiency under different ecosystems, Publications from USDA-ARS, UNL Faculty Paper **532** (2001).

[3] JOHNSON, D.E., et al., The influence of rice plant type on the effect of weed competition on Oryza sativa and Oryza glaberrima, Weed Res. 38 (1998) 207–216.

[4] BALASUBRAMANIAN, V., et al., Integrated crop management for enhancing yield, factor productivity, and profitability in Asian rice farms. Int. Rice Comm. (FAO) Newsletter 54 (2005) 63–72.

[5] VERDOUW H., et al., NH_3 determination based on indophenol formation with sodium salicylate, Water Res. **12** (1978) 399–402.

[6] HUFFMAN, S.A., BARBARIC K.A., Soil nitrate analysis by cadmium reduction, Comm. Soil Sci. Plant Anal. **12** (1981) 79–89.

[7] RISGAARD-PETERSEN, N., RYSGAARD, S., Nitrate reduction in sediments and water-logged soil measured by ^{15}N techniques, In: Alef, K. and Nannipieri, P. (Eds.), Methods in applied soil microbiology and biochemistry, Academic Press, London, UK (1995) 28–295.

[8] NICOLAISEN, M.H., et al., Nitrification-denitrification dynamics and community structure of NH_3 oxidizing bacteria in a high yield irrigated Philippine rice field, FEMS Microb. Ecol. **49** (2004) 359–369.

[9] DALSGAARD, T., et al., Protocol Handbook for NICE, Nitrogen Cycling in Estuaries, National Environment Research Institute, Silkeborg, Denmark (2000) 43–50.

[10] HAYASHI, K., NISHIMURA, S., YAGI, K., NH_3 volatilization from the surface of a Japanese paddy field during rice cultivation, Soil Sci. Plant Nut. **52** (2006) 545–555.

[11] WATANABE, T., et al., Measurement of NH_3 volatilization from flooded paddy fields in Viet Nam. Soil Sci. Plant Nut. **55** (2009) 793–799.

6 CONCLUSIONS

IAEA Rice Production Guidelines for Irrigated and Rain-fed Lowlands of Asia

Rice has been the life-line of Asia since its domestication about 10000 years ago. Close to 90% of the world's rice is produced and consumed in Asia. Millions of farmers are involved in growing rice and they have been developing and exchanging new rice varieties and production technologies within and between the countries of Asia and the rest of the world for generations. The modernisation of rice farming in Asia is critical to ensuring an adequate supply of rice for both current and future rice consumers. The greatest challenges to agricultural scientists will be how to intensify the production of rice without harming the environment, while at the same time adapting farming systems to both a changing climate and a dwindling land and water resource base. Basically, what Asia needs are 'climate-smart' rice varieties for use together with sustainable, land and water resource-conserving, rice production technologies.

IAEA's Rice Production Guidelines for Asia attempts to serve the different Asian countries by bringing together a concise information package on 'improved' rice varieties and the technologies on rice production and post-harvest procedures which have been developed during the past five decades by IRRI, Philippines in close collaboration with the different Asian national R&D institutes. These Guidelines are intended to assist farmers in learning how to adapt the new 'climate smart' rice varieties and the production and post-harvest technologies that are most suited to their own circumstances in the various regions and countries of Asia, help researchers to further improve the best management practices for rice and the role of nuclear techniques to quantify N use efficiency and better understand the pathways of GHGs emission.

If adopted successfully, the use of these 'climate smart' rice varieties can increase farm productivity and profitability, while also maintaining a resource base which will allow sustained rice production over the long term.

The Guidelines emphasise the importance of initially using high quality seed for uniform crop establishment. Specific directions are provided on how farmers can best develop 'nurseries' for raising rice seedlings for transplanting, and how to prepare the main field prior to transplanting young rice seedlings. The Guidelines also describe the sowing of dry or pre-sprouted seeds and point out the pros and cons of transplanting of young rice seedlings, versus the direct seeding of dry or pre-sprouted rice seeds directly into the main field.

The Guidelines note that regular and timely irrigation is critical for obtaining high yields of rice grain in irrigated lowland fields, in order to ensure there is no water deficit from the stage of panicle initiation to grain filling. For rainfed lowlands a better management of the variable rainfall is a major objective, one which can often be accomplished by rainwater harvesting and storage of excess rainfall in farm ponds. There it will be available for supplementary irrigation during later dry periods in semiarid regions. And, by the skilful management of floods through proper drainage, a guided direction of excess rainwater to farm or community ponds and check dams may be possible.

Integrated and crop-need-based nutrient, weed, insect pest and disease management is covered fully in the Guidelines. By using these improved crop management methods, farmers can optimise crop yields, minimise production costs, and protect the environment by releasing less GHGs and leakage of nutrients. Finally, the Guidelines note that a timely harvest and proper post-harvest processing will minimise grain losses and maximise market value of rice grain and other rice products.

ABBREVIATIONS AND ACRONYMS

Al	Aluminium
AS	Arsenic
ANOVA	analysis of variance
AWD	alternate wetting and drying
BB	Bacterial Blight
BD	Bulk density
BPH	brown plant hopper
C	Carbon
CA	Conservation Agriculture
Ca	Calcium
ca.	Circa, around
CF	continuous flooding
CH_4	Methane
cm	centimeter
CO	Carbon monoxide
CO_2	Carbon Dioxide
Cu	Cupper
cv.	Cultivar
DAS	day after sowing
DAT	days after transplanting
DDS	Dry direct seeding
df	degree of freedom
DS	dry season
DW	dry weight
FAO	Food and Agriculture Organization of United Nations
Fe	Iron
FNUE	Fertiliser N use efficiency
g	gram

GA_3	Gibberellic acid
GHGs	Greenhouse gases
GLH	green leaf hopper
hrs	hours
ha	hectare
He	Helium
HYVs	High-yielding varieties
IAD	intensive agricultural development
IADPs	Intensive Agricultural Development Programmes
IAEA	International Atomic Energy Agency
IRRI	International Rice Research Institute
IITA	International Institute of Tropical Agriculture
INM	Integrated nutrient management
IPM	Integrated pest management
IQ	intelligence quotient
K	Potassium
KCl	Potassium chloride
Kg	Kilogram
L	litre
M	Molar
mg	milligram
m^2	square meter
m^3	Cubic meter
m	meter
mm	millimeter
ml	millilitre
mM	milli molar
µm	micrometer
µmol	micro mole
mha	million hectare

mt	million tonnes
Mg	Magnesium
MC	moisture content
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
NH_4	ammonium
NH_3	ammonia
NH_2	diamnine
N_2O	Dinitrogen monoxide
NO	Nitric oxide
N_2	dinitrogen)
NO_X	Knox (NH3, NO, N_2O, NO_2 and N_2)
NO_3	Nitrate
NPK	Complex fertiliser comprised of nitrogen, phosphorus and potassium
O_3	ozone
O_2	Oxygen
P	Phosphorus
PCRC	Per Capita Rica Consumption
pH	measure of acidity or alkalinity of a solution
PM	particulate matter
PTFE	polytetrafluoroethylene
PPP	public private partnership
ppm	parts per million
PVS	participatory variety selection
rpm	revolution per minute
RGM	rice gall midge
RTV	rice tungro virus
RLR	rain-fed lowland rice

S	Sulphur
Si	Silicon
SECC	Socio-economic and Caste Census
SSNM	Site specific nutrient management
SRT	Saguna Rice Technique
SWMCN	Soil and Water Management and Crop Nutrition
t	tonne
UV	ultraviolet
UR	Uppland rice
vol	volume
WBPH	white bagged plant hopper
WS	wet season
YAAS	Yunnan Academy of Agricultural Sciences
yr	year
Zn	Zinc
°C	degree centigrade

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