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Achieving sustainable cultivation of rice

Volume 2: Cultivation, pest and disease management

Edited by Professor Takuji Sasaki
Tokyo University of Agriculture, Japan

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Introduction

Rice (*Oryza sativa* L.) is a principal food for over 3 billion people (around half the global population), providing up to 23% of calorie requirements worldwide, and is the staple food for the 70% of the world's poor living in Asia. Rice is cultivated in more than 100 countries across the world on around 154 million hectares annually, equal to 11% of the world's cultivable land. It has been predicted that global demand for rice will increase from 479 million tons in 2014/15 to as much as 551 million tons by 2029/30. At present, the increase in rice production rate (at under 1% per year) is lower than the increase in population of 1.5% per year. The rice community therefore faces the challenge of increasing rice production by 25-50% over the next thirty years, in the face of a rising population, plateauing rice yields, pressures on land and other resources available for rice cultivation and an unstable, changing climate. The two volumes of *Achieving sustainable cultivation of rice* summarize some of the key research addressing this challenge. This volume (Volume 2) focuses on developments in cultivation techniques and pest management in making production more efficient and sustainable. Volume 1 reviews developments in breeding to improve yields as well as research on improving nutritional and other aspects of quality.

Part 1 Rice cultivation techniques

The majority of the world's rice is grown under irrigated conditions in which the fields are flooded from planting to harvest. Rice land receives 35–45% of all the world's irrigation water (which itself uses around 70% of all the world's developed water resources). In view of the importance of rice and growing concerns about future water scarcity, achieving water savings in irrigated rice production has become one of the key research challenges for the rice-growing world.

As Chapter 1 points out, there are a number of potential research avenues being pursued to achieve water savings without sacrificing rice yields. These avenues include:

- breeding short-duration, high-yielding modern rice varieties which require less water due to less time growing in the field (discussed in Chapters 3–5 in Volume 1 of *Achieving sustainable cultivation of rice*)
- breeding and cultivation of varieties which yield better in harsh environments (such as higher salinity or drought conditions – discussed, e.g., in Chapter 3 in this volume and Chapter 6 in Volume 1)
- precision agriculture, site-specific nutrient management (SSNM) and improved crop establishment methods to increase yields and minimize wasted resources (reviewed, e.g., in Chapters 2, 6 and 7 in this volume)
- improved irrigation techniques which minimize unproductive water losses in the cropping system (reviewed in Chapter 1)

Essentially the aim of any water-saving technique is to increase irrigated water productivity (WP), the amount of rice produced per unit of irrigation water applied. At the field level, water is either stored in the soil matrix, transpired to the atmosphere via the crop, lost by evaporation directly from the soil or water surface, or lost from the system via a number of other possible mechanisms (such as deep drainage below the reach of crop roots, lateral flows out of the field which include surface runoff or seepage under the bunds, etc.). Any attempts to save water must take account of factors such as evapotranspiration (ET) from soil and plants which takes water out of the system.

In the Indian state of Punjab, for example, declining water table depth has been a major concern for decades due to over-exploitation of water resources (particularly pumping of groundwater). Numerous water-saving practices have been suggested to save irrigation water and contribute to arresting the decline (such as laser land levelling, alternate wetting and drying (AWD) techniques, conservation agriculture practices, raised beds, delayed rice transplanting or shorter-duration rice varieties). These irrigation water-saving techniques can achieve water savings at the field scale. However, it has been suggested that irrigation water-saving options which primarily reduce ET (such as residue retention to reduce soil evaporation) are most likely to succeed in addressing the problem in Punjab, where evaporative losses are the true losses in this system at the regional scale which are driving the water table decline.

Chapter 1 discusses three water-saving techniques: aerobic rice systems, AWD, and saturated soil culture (SSC). These can be ranked according to levels of water availability, starting with aerobic rice systems. Further up the spectrum towards fully ponded lowland rice systems (which may be rainfed or irrigated) are interim irrigated practices such as AWD and SSC.

Aerobic rice is a term introduced by the International Rice Research Institute (IRRI) for high-yielding rice grown under non-flooded conditions in non-puddled and unsaturated (aerobic) soil. In an aerobic rice system, the crop can be dry direct seeded or transplanted and soils are kept aerobic throughout the growing season. Supplemental irrigation is applied as necessary, for example using sprinkler irrigation, furrow irrigation on beds, and drip and subsurface irrigation. The use of surface mulches in aerobic rice systems has been noted to increase irrigation water productivity. Studies have suggested that, by reducing water use during land preparation and limiting seepage, percolation and evaporation, aerobic rice had 51% lower total water use and 32–88% higher water productivity, expressed as gram of grain per kilogram of water, than flooded rice. When specific aerobic cultivars are grown under aerobic conditions and compared with specific lowland cultivars grown under lowland conditions, the reported WP gains are even higher. The WUE of the aerobic varieties under aerobic conditions can be 164–188% higher than that of lowland cultivated rice varieties. A key problem in aerobic rice cultivation is yield decline resulting from continuous cropping of aerobic rice, due to factors including build-up of pests such as nematodes and the loss of soil organic carbon reserves. These problems can be offset by techniques such as crop rotation, better nitrogen (N) management and cultivar improvement. Dry-seeded and aerobic cultivation of rice are both discussed in Chapter 4 in this volume.

An established irrigation water-saving technology for rice is AWD, based on the fact that high yields in rice can be achieved without continuous flooding. It has been demonstrated over many years in numerous environments that rice can extract adequate water from the soil around roots even in the absence of standing water in the field. In AWD, once the crop is established, the pond depth is allowed to fall to a threshold depth below the surface of the soil for a certain period before the next irrigation is applied. As chapter 1 shows, AWD improves water productivity (WP) universally when applied within recommended guidelines. However, research varies in terms of AWD's impact on yields. AWD is unlikely to be a key solution to the crisis of falling water tables in regions such as the Indian

Northwest, where technologies to decrease ET are the main objective. However, in areas where deep percolation losses are effectively lost from the farmer's irrigation system, AWD water savings may be a real solution to water-shortage problems.

SSC is an irrigation practice which involves keeping the rice-growing soil saturated but not ponded throughout the growth period, thereby reducing the hydraulic head of the water, and in turn reducing the percolation rate and water lost to deep drainage. SSC is the typically nominated water management method in the system of rice intensification (SRI), which is reviewed in detail in Chapter 7 in this volume. Studies show a wide range of water savings of between 9 and 40%, depending on factors such as soil permeability. The literature also indicates that, in combination with AWD, SSC has the potential to increase water savings to over 50%.

Chapter 1 concludes with a case study of the use of AWD in growing japonica rice in temperate southeast Australia. It shows how research has been able to establish the optimal level of moisture stress between irrigation periods to save water without compromising yields. Locally targeted research to fully understand the interactions between crop, management and environmental constraints, and then to subsequently use this understanding to optimize practical advice to farmers, represents the greatest challenge to researchers in the field of irrigation water savings.

It has been estimated that rice accounts for up to 15% of total fertilizer use, a figure that rises to 20% in the case of the use of nitrogen fertilizer. Fertilizers account for 20 to 25% of total production costs in some rice systems. Due to large field-to-field variability in soil nutrition, the efficient use of fertilizers is not possible with the traditional reliance on broad-based blanket recommendations for their use. A key challenge for more efficient and sustainable rice cultivation is therefore a more targeted use of fertilizers. Chapter 2 provides a comprehensive review of the ways this is being achieved for nitrogen (N), phosphorus (P) and potassium (K).

SSNM for rice was developed in Asia by the IRRI as a plant-based approach for applying fertilizer to optimally match the needs of the rice crop in a specific field and season. The major focus of SSNM is on managing both temporal variability in plant nutrient status during the growing season and managing field-specific spatial variation in nutrient requirements. Given its importance, a particular focus is on N requirements, with requirements for P and K also taken into consideration. The chapter also discusses the targeted application of micronutrients such as zinc, iron, manganese and boron. Modelling has been used to predict soil nutrient supply and plant uptake at differing stages of crop growth. To ensure that supply of N matches the crop need at critical growth stages, the estimated total fertilizer N requirement by rice crop is then apportioned among multiple application points during the growing season ('fixed-time/adjustable dose').

A key element in achieving SSNM is the development of diagnostic tools that can assess 'real-time' requirements of rice for N and other nutrients. The chapter reviews the development and use of non-invasive, optical methods based on leaf greenness, absorbance and/or reflectance of light by leaves. These include leaf colour charts (LCC); chlorophyll meters; ground-based sensors; and digital, aerial and satellite imaging techniques. The chapter discusses the principles and application of chlorophyll meters, LCC and optical sensors in detail. Both 'real-time' and 'fixed-time/adjustable dose' methods can be used to target N, P and K application more precisely.

In addition to investigating better control of the timing and amount of fertilizer, research has also looked at how it can be better delivered. One of the reasons for the low fertilizer use efficiency of water-soluble N fertilizers such as urea, ammonium sulphate and ammonium carbonate in rice is the imbalance between the timing and degree that fertilizer is delivered to plants and the actual demands of the crop. Slow- and controlled-release N fertilizers increase N use efficiency and rice yields whilst reducing fertilizer losses because they synchronize N availability with plant demand. Slow-release fertilizers consist of compounds of generally low water solubility, which become available on enzymatic hydrolysis by urease or other biological catalysts. The N release patterns, rates and duration of slow-release fertilizers are thus strongly dependent on soil properties and environmental conditions such as moisture and temperature. Controlled-release fertilizers consist of highly soluble urea pills or granules coated with a water-insoluble material such as sulphur or polyolefin that control the rate, pattern and duration of N release. Besides the advantages of controlled-released fertilizers in reducing N losses to the environment and increasing fertilizer N use efficiency in rice, the rate of N application or the number of applications during the growing season can also be reduced, which has the added advantage of saving labour costs.

There is considerable interest in the use of urease and nitrification inhibitors in rice systems because urea is the most important conventional N fertilizer for rice and N loses via NH3 volatilization and nitrification–denitrification significantly contribute to low fertilizer use efficiency. The short-lived effect of the inhibitor is a limitation when urea is applied to flooded rice and further research is needed to improve our understanding of when urease and nitrification inhibitors can be used most cost-effectively. Placement of fertilizer nutrients, particularly deep placement in the soil, is also crucial to increase rice yield because it minimizes N losses. The chapter reviews research on the effective use of urea supergranules (USG) and band placement of liquid urea using mechanical injection techniques.

Finally, as the chapter shows, organic manures have regained importance as components of integrated plant nutrient management (IPNM) strategies. A return to managing soil fertility through the combination of organic resources and mineral nutrient inputs has become one of the key features of sustainable soil management. The basic concept underlying IPNM is the maintenance and improvement of soil health for more sustainable, long-term crop productivity with fertilizers used as a supplement to nutrients supplied by different organic sources available at the farm to meet the nutrient requirement of the crops. The maintenance and/or improvement of organic matter in soil is central to the philosophy of IPNM, using inputs such as farmyard manure, crop residues, sewage sludge or food industry wastes. During the last two decades, many studies of rice cultivation in South Asia have shown the positive impact on rice yields from integrated management of different organic and mineral fertilizer inputs. Future challenges include reducing the costs and simplifying SSNM procedures for rice farmers without losing their ability to target fertilizer use more effectively as well as refining IPNM to integrate different sources of nutrition.

As mentioned in Chapter 1, a major challenge in rice cultivation is cultivation in less favourable environments, given both the limits to productivity gains in established irrigated rice environments and the likely impact of climate change. Chapter 3 reviews how to optimize rice cultivation in saline, flood-prone coastal areas, using West Bengal in India as an example. It builds on topics in both Chapters 1 and 2, for example irrigation and nutrient management as well as improving soil health through conservation agriculture techniques. It also demonstrates the importance of an integrated and holistic approach from the use of appropriate varieties to better cultivation, nutrient and irrigation management practices.

The chapter first explores the development of improved, salt-tolerant varieties using mutagenic techniques to cross local landraces as well as the shift to growing salt- and flood-tolerant varieties during the wet season whilst using salt-tolerant short-duration varieties during the dry season. It also explores the role of improved agronomic practices such as raising healthy seedlings through proper nursery management techniques such as optimal seeding density and nutrition. It also reviews better methods for planting, whether transplanting of aged seedlings during the wet season or the use of drum seeders for early, more efficient crop establishment during the dry season. Weed management is also covered, a subject discussed in detail in Chapter 14.

Building on Chapter 2, the chapter also reviews the use of IPNM using combined organic and inorganic sources of nutrition, including farmyard manure and biofertilizers such as *Azotobacter*, *Azospirillum* and blue green algae. It also discusses the role of cover crops such as the legume *Sesbania aculeata* and *Azolla*, a free-floating freshwater fern which fixes nitrogen in the soil and inhibits salt movement into rice plants, as well as inorganic nutrition such as deep placement of USG. The chapter discusses other aspects of conservation agriculture such as mulching during dry season using rice husk and straw or organic farm waste, for example, as well as techniques for leaching of excess soluble salts from the root zone of crops and ways of adapting SRI techniques (a topic discussed in Chapter 7).

Direct seeding (also known by the acronym DSR (direct-seeded rice)) is an alternative to more traditional transplanting techniques particularly suited to rainfed regions. Seeds are sown on a dry or moist non-puddled soil surface, and then incorporated by ploughing or harrowing. Key issues in successful dry direct seeding include effective land levelling (e.g. to ensure effective irrigation) and good crop establishment (to ensure optimum plant density), for example, by optimizing planting date, seed treatment, seed rate and planting depth. Other issues include precise water management (especially in the early stages of growth to ensure good rooting and seedling growth) and effective weed management (to avoid competition with young rice plants). The chapter reviews good agricultural practices (GAP) in DSR, from cultivar selection and soil preparation to seed treatment and sowing, irrigation and fertilization, thinning, weed management and harvesting.

As highlighted in Chapter 1, aerobic cultivation is a water-saving production system in which rice is grown in well-drained, non-puddled and non-saturated soil conditions. The main advantages of aerobic cultivation include reduced water use, lower labour requirements and costs, the need for fewer seeds, improved efficiency in fertilizer use and preservation of soil texture and quality. Challenges facing aerobic rice cultivation include lower yields compared to traditional transplanting and competition from weeds. The chapter summarizes GAP techniques to address these issues.

The final chapter in Part 1 looks at the handling of by-products from rice production. As Chapter 5 points out, each kg of milled rice results in roughly 1.4 kg of rice straw and 0.28 kg of husk. Rice straw is separated from the grains after the plant is threshed whilst rice husk is a by-product in the milling process. The intensification of rice cropping systems with the increased use of combine harvesters and shorter breaks between crops has both significantly increased the volume of these by-products, made collection more difficult and complicated the traditional use of straw as a soil amendment. This has resulted in an increase in straw burning with damaging consequences for soil health and the environment. The chapter looks at ways of overcoming these problems such as speeding up straw decomposition during breaks between crops and the development of rice straw baling systems to collect straw more easily. The chapter also reviews ways of using the by-products, for example to generate fuel, heat or electricity through thermal, chemical or bio-based processes. It includes illustrative case studies on rice husk combustion for paddy drying, power generation from rice straw combustion, conversion of rice straw to biochar for use as a soil amendment, cultivation of mushroom on rice straw and the use of rice straw for livestock feed.

Part 2 Overall management of rice cultivation

The range of techniques discussed in Part 1 can only be effective if there are methods for accurately assessing yield gaps and their causes, setting targets for improvement and measuring improvements in productivity. Chapter 6 starts by reviewing differing definitions of yield, starting with 'potential yield', defined as the maximum yield that can be obtained from a crop in a given environment. As the chapter points out, there are other yield benchmarks, namely 'economic yield', 'experimental yield' and 'best farmers' yield' which lie between potential yield (or water-limited potential yield) and average on-farm yield.

The chapter provides a valuable overview and comparison of existing yield gap studies such as the results of the Global Yield Gap Atlas (GYGP) programme for rice, what they show and their degree of reliability. It looks first at studies focusing on the quantification of yield gaps, then describes studies concentrating on identifying the causes of yield gaps. Examples are mainly from sub-Saharan Africa, where yields have been historically low, though research here mirrors similar results from South Asia. The chapter discusses the various methods for investigating causes, including crop simulation models, use of survey data and farm experiments. Research has shown a broad range of factors contributing to yield gaps, including:

- Biophysical (weather, soil, water, pest pressure, weeds);
- Technical/management (labour availability, timing of operations, tillage, variety or seed selection, management of water, nutrients, weeds and pests, and harvesting);
- Socio-economic (social and economic status, farmers' cultural traditions, commitments and obligations, knowledge, family size and farm profitability);
- Institutional and policy (government policy, rice price, credit, input supply, land tenure, markets, research, development and extension);
- Technology learning and linkages (competence and resources of extension staff; knowledge and skills; linkages among public, private and NGO extension staff).

One illustration comes from the Senegal River Valley which identified how delayed sowing resulted in a yield reduction of around 1 t/ha and the reasons behind this delay such as availability of credit, machinery and irrigation water. The chapter concludes by reflecting on the ways in which different approaches can be used and how they can complement each other. It concludes with a discussion of the challenges to achieving better quantification of yield gaps and their causes, and the implications of yield gap studies for sustainable agricultural development to meet future rice demand. As it points out, rapid advances are being made in remote sensing technology for estimating various parameters such as soil quality, cropping season and water availability. Combined with the expected increase in sources of reliable weather data and improved bias correction for satellite-based weather data, advances in technology will enable the development of crop models of potential and water-limited yield that are applicable to a wide range of spatial scales.

Chapter 7 reviews one of the best-known and controversial systems of rice production: SRI which, from its origins in Madagascar some 30 years ago, is now used in over 50 countries. SRI involves practices such as:

- transplanting single, young, widely spaced seedlings, typically in square patterns
- keeping soil mostly wet but not flooded, either with small daily applications of water or with AWD techniques (as discussed in Chapter 1)
- controlling weeds mechanically, both to protect the crop and aerate the soil
- enriching the soil with organic matter

The principles underlying SRI can be summarized as:

- early crop establishment with healthy plants and minimal competition between plants to promote growth of root systems and canopies
- promotion of soil health/fertility
- management of water to avoid anaerobic soil conditions

SRI has allowed a significant reduction in use of inputs such as water and fertilizer. It can be seen as sharing a common foundation with conservation agriculture. Written by one of the world's foremost authorities on SRI, the chapter reviews the origins and spread of SRI as well as more recent developments such as the use of direct seeding for crop establishment and mechanization of SRI operations. The chapter also provides a detailed assessment of the types of yield achieved by SRI in different conditions and provides a careful review of the sometimes conflicting results on how it compares with other types of rice cultivation practice.

The final chapter in Part 2 picks up on resource efficiency and sustainability issues explored in the chapters in Part 1 as well as other chapters such as Chapter 7 on SRI. As noted earlier, rice cultivation consumes significant amounts of irrigation water, fertilizers and other inputs such as pesticides. Sustainability issues in rice cultivation include:

- resource use efficiency (land, water, agrochemicals, labour)
- climate change impacts
- impacts on ecosystem services
- soil impacts (e.g. salinization)

Flooded rice cultivation (irrigated, rainfed and deep-water cultivation) also represents an important source of atmospheric methane and, to a lesser extent, nitrous oxide. Rice cultivation not only has a significant environmental impact but is, itself, vulnerable to the effects of climate change. This makes it critical to make rice cultivation more sustainable as it seeks to improve yields.

As Chapter 8 indicates, voluntary sustainability standards (VSS) have emerged as an important tool to promote more sustainable practices in agri-food systems. However, progress in rice has been slow, in part because, with a low-value bulk commodity such as rice, compliance costs cannot easily be borne by small, resource-poor farmers. In addition, with less than 2% of global rice production destined for high-value markets, there has been less consumer pressure for sustainability initiatives.

This has led organizations such as the United Nations Environment Programme and the IRRI to launch the sustainable rice platform (SRP) in 2011 to promote adoption of sustainable climate-smart best practices in rice cultivation. Such practices include:

- AWD and other ways of improving irrigation (discussed in Chapter 1)
- Multi-stress-tolerant varieties (reviewed, e.g., in Chapter 6 in Volume 1)
- SSNM (discussed in Chapter 2)
- Methods for sustainable intensification of rice cropping systems (such as SRI) (reviewed in Chapter 7)
- Biofortification initiatives (surveyed in Part 2 of Volume 1)
- Low-cost post-harvest technologies to manage residues and reduce food losses (discussed in Chapter 5)

A set of quantitative indicators (SRP performance indicators for sustainable rice cultivation) has been developed by SRP stakeholders to provide a system for objective measurement of the benefits and impacts of adopting good environmental practices in such areas as greenhouse gas emissions, water, nutrient and pesticide use efficiency. This allows farmers to work towards the SRP standard for sustainable rice cultivation. This was launched in 2015 as the world's first VSS for rice, serving to both define what constitutes sustainability and promote improvement. By incorporating a scoring system, the standard allows for stepwise improvement in order to encourage and reward progress towards full compliance. The current standard is currently undergoing an extensive multi-country field validation programme in Brazil, Cambodia, China, India, Indonesia, Myanmar, Pakistan, the Philippines, Thailand, Uganda and Vietnam. The findings of the validation programme will be used to revise the standards and indicators, and then define targets and voluntary/mandatory levels of compliance for each requirement, with the aim of providing a viable path to improving sustainability.

Part 3 Rice pests

The final part of the book reviews key pests which limit rice yields and measures for their management. As Chapter 9 points out, the rice plant is an ideal host for many insect species. There are over 800 insect species which damage rice in one way or another, although the majority of these species do not cause a significant problem. In tropical Asia, about 20 species are of major importance. In Africa, 15 species of insects are considered serious pests of rice whilst about 20 species cause significant damage in the Americas. To develop effective pest management strategies, it is essential to properly identify and to understand the biology and ecology of major insect pests. This chapter utilizes the unique knowledge and expertise of leading rice entomologists from Africa, Asia and the Americas to provide the first global overview of rice insect pests. The chapter reviews insects based on the following feeding types: root and stem feeders, stem borers, rice gall midges, leafhoppers and planthoppers, foliage feeders and panicle feeders. In each case, the chapter provides a summary of each type together with a case study of a particular insect. The case studies cover the rice water weevil, rice striped borer, Asian rice gall midge, brown planthopper, African rice hispa and rice bug. The discussion of each insect includes geographical distribution, plant hosts other than rice, description and biology, plant damage and ecology.

With Chapter 9 as a context, Chapter 10 reviews techniques for managing insect pests. The chapter suggests a four-phase framework for the integrated management of insect pests, starting with measures to prevent damaging levels of pests (phases 1 and 2) and thus minimize the need for curative actions (phases 3 and 4). There are two main types of preventative strategy: 1) cultural practices that directly target insect pest populations (primary practices) and 2) crop husbandry practices with secondary effects on pest populations (secondary practices). Practices that directly target insect pest populations include mechanical and physical removal of insect pest populations.

Among cultural practices for pest management, deployment of host-resistant plants (a primary cultural practice) and fertilizer management (a secondary cultural practice) form basic building blocks in developing a rice ecosystem with reduced vulnerability against insect pests. As Chapter 10 points out, much work has been done to identify resistance genes, especially against hemipteran pests, and breed them into elite varieties. The chapter refers to several general deployment strategies to improve the durability of resistance genes against pests and diseases: gene rotation, field mixture of resistance genes and gene pyramiding. In general, fertilizer management affects rice insect pest populations by modifying rice plants' suitability for and attractiveness towards herbivorous insects as well as their enemies.

Phases 3 to 4 (which seek to remove rather than prevent pests) cover chemical and biological control of pests. High usage of pesticides potentially damages populations of predators which prey on insect pests and can result in resistance among pests. Conservation biological control aims to remedy this situation by limiting insecticide use, promoting selective insecticides and altering crop habitats to allow better support for natural enemy populations. Various habitat management schemes, for example, intercropping and introduction of wildflower strips or plants repellent to herbivores, have been shown to disrupt pests, enhance natural enemies and reduce crop damage. In contrast to conservation biological control, the aim of which is to improve the impact of indigenous natural enemy community, augmentative biological control typically aims for a limited-time increase in specific natural enemy species to temporally suppress pest populations and avoid economic damage in yield. Augmentative biological control is usually achieved by field releases of predators, parasitoids or pathogens with expected effects to last either season-long (inoculative biological control) or within a short period of time during the season (inundative biological control).

Finally, Chapter 10 reviews ways of disseminating these management practices through farmer field schools (FFS) and mass media campaigns (MMC). FFS and MMC complement each other by creating a nucleus of farmers with in-depth understanding of agro-ecosystem management and the ability to conduct their own field experiments, while mass communicating simpler pest management messages towards a larger farming audience.

As Chapter 10 shows, even when seeking to keep their use to a minimum, insecticides remain a component of pest management alongside other methods of control. This theme is reiterated in Chapter 11 which argues that the use of plant protection products (PPPs) such as insecticides, herbicides and fungicides is still a key component in ensuring the sustainability of rice cultivation. It is essential to evaluate the risks these products pose to human health and the environment, and to determine what measures are required to keep the risks within acceptable limits. Chapter 11 reviews how the risks posed by PPPs are currently evaluated, focusing on the importance of multi-tier assessments and the range of available simulation models, and considers where current risk assessment practices require improvement. Methods of managing the risks associated with PPPs and encouraging more sustainable rice cultivation are then discussed, using the example of the European Sustainable Use Directive which emphasizes the importance of integrated pest management (IPM) and how IPM strategies can be implanted in practice by farmers.

Chapter 12 builds on Chapters 9 through 11 by looking in more detail at key issues and challenges in implementing IPM strategies in practice in rice cultivation. As the chapter points out, rice cultivation in many parts of the world has continued to depend significantly on pesticide use. However, the trend towards an increasing availability of pesticides has not resulted in correspondingly lower pest and weed incidences or sustained yield improvements. Instead, it has led to area-wide problems of resistant pests and weeds, sustained outbreaks, for example, of planthoppers and leaffolders, problems in managing other pests such as snails, and concerns about the wider impact of pesticides on environmental and human health.

A key reason for the continued threat from pests is that the efficiency of natural enemies such as spiders and predatory wasps is reduced by insecticides, either because they are killed by the chemicals or because their behaviours are altered. Increased pest reproduction and reduced mortality leads to exponential population growth rates in high-fecundity species such as planthoppers and leaffolders, a phenomenon known as 'resurgence'. Many scientific reports have described pesticide-induced resurgence in a range of rice pest insects including planthoppers, stemborers and leaffolders, as well as paddy-dwelling species of health concern such as mosquitoes.

The chapter identifies three main ingredients for successful IPM application. The first of these is knowledge of the rice production system, its component species (including the rice plant) and the nature of interactions between these species. It is also essential to understand how rice ecosystems, particularly their pest and weed populations, are regulated through negative feedback loops which can lead, for example, to problems of resurgence. The chapter introduces the concept of 'crop health syndromes' which emphasizes the need both to understand the complexity of host–plant interactions and, in consequence, to develop a holistic approach in pest management. As an example, several herbivores including insects, snails and rodents are associated with paddy field weeds, sometimes facilitating the weeds by reducing shade from the rice canopy. Weeds may in turn lead to increased damage to rice from birds, as has been noted from recent studies in Africa. In different conditions, certain 'pests' may become beneficial 'allies' because of their predatory or herbivore roles, for example, apple snails may increase rice production costs by damaging young seedlings in flooded rice systems, but can play a major role in reducing weed biomass during later crop stages. IPM can only be effective if these interactions are properly understood.

An example of the importance of understanding of these interactions can be seen in research on the way cultural practices such as use of fertilizers affects pests and their management. As discussed in Chapter 10, field and laboratory studies have indicated higher levels of damage from insects, snails and weeds to rice produced under high nitrogen conditions. The structure of weed communities (relative abundance and species richness) may also significantly change under high nitrogen conditions. Farmers who adopt high-yield varieties, particularly hybrid rice varieties, will often use higher amounts of fertilizer to meet the yield potential of the varieties. Hybrid rice has therefore been associated with higher incidences of several pests and diseases, including stemborers and planthoppers.

Building on a full understanding of pest ecology, the second key component of a successful IPM strategy is a set of tools to boost natural regulation of pests and avoid triggering damaging crop health syndromes. A precondition for using IPM techniques successfully is effective detection and monitoring of pests. As an example, the chapter highlights the use of light traps to determine the extent, direction and climatic conditions that generate planthopper migrations and to act as an early warning system for rice farmers before planthoppers alight in their fields. Recent research has attempted to develop technologies to better detect pests including using remote sensing applications. It will be necessary to continually update damage thresholds and estimated yield losses as climates and crop management practices change and because different rice varieties often have specific responses to pest attack.

The chapter provides a detailed review of research into different IPM tools. These range from developing and evaluating botanical pesticides such as those derived from the neem plant, to the development of synthetic pheromones to disrupt the life cycles of pests such as striped stemborers and ricebugs, or repellents such as methyl anthranilate, pulegone and caffeine. Biocontrol of insects and snails using ducks and fish has also gained recent attention as part of integrated farming systems. Building on Chapter 10, the chapter reviews recent research on the use of augmentative biological control for the control of rice field insects, nematodes and storage pests. These studies have focused on the development of rearing and application methods for *Trichogramma* spp. to control stemborers for example, and the use of bacteria such as *Pseudomonas fluorescens* to control insects, nematodes and rice diseases. Among the advantages of using fungal and bacterial biocontrol agents are the ease with which they can be reared and the facility with which they can be applied in the field. However, they do exert selection pressure for pest adaptation if used in excess.

An important element of IPM is to encourage predators of insect pests. Ecological engineering research in Asia has mainly focused on creating flower strips and vegetable patches as a source of alternative foods and refuge for the natural enemies of planthoppers and stemborers. Recent reports have indicated that such systems can successfully increase rice yields, reduce pest damage, reduce or eliminate pesticide inputs, increase the biodiversity and function of predators including predatory birds, and increase farm profits and food production by using the space available on rice bunds (levees) to grow vegetables.

Another element in an IPM arsenal is the development of pest-resistant varieties. In a recent study, for example, researchers from South and Southeast Asia evaluated the effectiveness of several donor varieties with known resistance genes against the brown planthopper. Their results indicated that most genes were now ineffective, but that traditional varieties and landraces containing two or more resistance genes remained largely effective. This supports the idea that pyramiding resistance genes can improve the durability of anti-herbivore resistance. Following the development of Bt-transgenic crops with resistance against chewing insects, transgenic resistance has become a major focus of research into reducing stemborer and leaffolder damage in rice. Transgenic rice expressing lectins, protease inhibitors and venoms have also been considered to combat rice planthoppers and other rice pests. More recently, research into RNAi technology has gained some attention for controlling planthoppers and stemborers.

However, it is clear that more research is required to bring the different 'technologies' together into functioning and sustainable rice production systems. Research into ecological engineering and biocontrol has rarely incorporated innovations in pest-resistant varieties whilst breeding initiatives often produce a resistant variety without considering how it can best be deployed within an overall IPM programme. Future research might benefit from more successfully integrating such diverse components of pest management.

The third and final key component of successful IPM is effective communication of knowledge and guidance of farmers towards best management practices. IPM is therefore as much about communication networks, effective teaching and extension activities, and agricultural policy as it is about ecology or technology. Research suggests that the main reasons for non-adoption of IPM include knowledge-related issues (lack of training, little technical support or limited availability of information), structural issues (lack of government policy and support, or limited funding) and implementation issues (prohibitive costs, limited access to inputs or over-complex systems). As an example, a lack of adequate extension support and of basic ecological knowledge means that farmers often initiate pesticide applications when they observe 'insects' or damage. However, they cannot distinguish pests from beneficial organisms, and cannot project from their field observations to realistic damage potentials. The result is inappropriate and ineffective pesticide application that may even do more harm than good.

Fortunately, there are initiatives to educate and support farmers in IPM implementation, such as the 'three reductions, three gains' (3R3G) campaign promoted through the Ministry of Agriculture and Rural Development in Vietnam which was successful in reducing pesticide inputs. The campaign promoted a reduction in seeding rates, fertilizers and pesticides to improve rice profitability. The chapter highlights other initiatives such as knowledge banks, digital information repositories with simplified retrieval interfaces to help users understand rice crop management and pest problems. In some cases specialized knowledge 'apps' have been made available to farmers through smart phones to help in pest identification and management, for example the Rice Knowledge Bank set up by the Bangladesh Rice Research Institute.

As Chapter 13 points out, rodents damage rice at all stages of crop development and are significant pests in all rice cropping systems: irrigated lowland, rainfed lowland, upland rainfed and deep-water/tidal wetlands. In some countries such as Indonesia rodents are considered the most important pre-harvest pest of rice, causing around 15% losses annually. In intensive lowland irrigated rice cropping systems rodents typically cause relatively low but regular losses each year. Probably of greater concern for smallholder farmers, however, are the episodic outbreaks that can lead to losses of 50-100% of the rice crop. In addition, post-harvest losses from rodents can be as much as 10-14%. Surveys of rice farmers highlight their concerns about rodents as a pest they find particularly hard to control.

There are a wide range of management options used for rodent management in rice systems. These can be categorized as physical, chemical and biocontrol techniques. The ultimate aim of a rodent management programme is to reduce the impact of damage rather than necessarily to eliminate pests completely. Chemical methods include acute and anticoagulant rodenticides. It is important to note that, for several years, no new rodenticidal compounds have been registered for use in crop protection. This has put greater emphasis on combining existing compounds as well as improving delivery mechanisms for rodenticides such as pulse baiting and pre-baiting to allow rats and mice to get used to feeding at a known site. As in the case of insects, knowledge of life cycles, foraging behaviour and food preferences is vital to the successful use of rodenticides. As an example, baits placed within rice fields are likely to be more attractive and more readily accepted during the tillering stage of the rice crop because food availability is low and pest rodents move into the rice field from the surrounding habitats during this time. However, the use of rodenticides can be limited by rodent behaviours such as neophobia (fear of new objects), conditioned aversion to the bait base or rodenticide, and the development of resistance. Other chemical methods include fumigation and the use of repellent compounds.

Limits in the use of chemical techniques have highlighted the importance of other approaches. Physical methods include trapping and barriers, including trap barrier systems or community trap barrier systems. Methods for the biocontrol or rodents include sterility control, reproductive inhibitors, parasites and diseases, though, in many cases, there has been limited research and commercial development. An example is the trialling of a rodent-specific parasite *Sarcocystis singaporensis* in rice fields in Thailand which resulted in reduced yield loss and demonstrated positive benefit-cost ratios similar to those obtained with conventional control techniques.

An important aspect of control is habitat management, including rice bunds (the small earthen banks surrounding rice field plots) which provide an important potential habitat for rodents. Effective management can be achieved through treatment of non-crop areas which are sources of habitat for rodents, including bunds or undisturbed weedy areas which provide burrows and nesting sites. This can be managed by slashing the weeds to reduce nesting habitat and increase predation risk. At a broad scale, crop synchrony is a highly effective form of management. For rodent species that exhibit a peak in breeding activity that coincides with the ripening stage of rice crops, crop synchrony limits the duration of this breeding period by reducing food availability. Habitat management can also be used to encourage predators such as owls.

Based on IPM principles, ecologically based rodent management (EBRM) is essentially a combination of the control methods mentioned above, but conducted in a way that takes proper account of the ecology and biology of the particular rodent pest species as well as the particular rice agro-ecosystem. To develop a successful rodent management strategy, it is important to identify the rodent species of concern and understand its ecology in the specific ecosystem. Key issues include the timing of control (to take advantage of stage of breeding and population abundance) and undertaking management over sufficiently large areas to reduce the chance of reinvasion after treatment.

Chapter 13 concludes with case studies of rodent control programmes in Vietnam, Laos and Tanzania. In the case of Vietnam, for example, farmers have traditionally relied heavily on the use of rodenticides and more informal techniques such as electrocution and spreading sump oil mixed with insecticides onto flooded rice fields to manage the rodent problem. These methods both have had limited success and have raised concerns about safety and environmental impact. To develop better programmes for rodent control, farming communities were trained and supported in implementing EBRM through “training-of-trainers” of local extension staff. A range of community-based rodent control options were trialled which were found to be relatively inexpensive to implement and resulted in reductions in yield losses. These include community actions such as synchronized cropping, rat control campaigns at key times, field hygiene and the use of community trap barrier systems when damage is expected to be high. After implementing EBRM, rodent damage was reduced by 33-50%, rice yields were increased by 2-5%, rodenticide use was reduced by 62-90% and the use of electrocution was reduced by 95%. Key lessons from implementing such programmes include the need to have good coordination between civic and government agencies to enable farmer participation, to have effective leadership of farmer groups and for management to be conducted early in the growth of the rice crop before rodent populations commence breeding.

Looking ahead, the chapter points out that improved monitoring systems and forecasting systems are urgently needed for EBRM. Most monitoring is conducted too late after damage has already occurred and there are very few predictive models available. There is strong interest in developing automated remote sensing equipment for rodents (in all crops, not just in rice). The challenge is making such equipment reliable and cheap, and not too data intensive. There is also interest in developing mobile phone applications for monitoring of rodents and provision of advice on better rodent control.

The chapter also reviews other vertebrate pests of rice such as birds. In some countries in Africa, birds are considered to be the second most important pest of rice after weeds. Preventative measures used to manage bird pests in rice include synchronous cropping, weed control (as weeds attract birds during the early grain filling stage) and nest destruction. Protective measures include the use of repellent substances, protecting fields or nurseries with nets or wires, and bird scaring techniques. However, aside from weed management, which has been shown to reduce bird visitation rates to rice fields, evidence that clearly demonstrate the effectiveness of these methods is limited.

As Chapter 13 points out, there are opportunities to explore the synergistic effects of management strategies with multiple benefits for rice production, for example concurrent weed and rodent management. It has also been shown that effective management of weeds also helps in managing insect pests and diseases. As Chapter 14 shows, rice grain yield losses caused by grasses can reach as high as 40%, with DSR systems particularly vulnerable. Continuous use of a particular cropping practice, such as repeated use of a particular herbicide, can inadvertently contribute to a shift in the dominance and distribution of weeds. Controlling weeds with only one or two techniques gives some weeds a chance to adapt to those practices. The use of herbicides with the same mechanism of action, year after year, has thus resulted in herbicide-resistant weed chemotypes. Repeated herbicide use may also result in weed flora shifting towards more persistent perennials, as well as a build-up of herbicide residues in the soil and in the harvested rice. Hundreds of weed species have now become resistant to major classes of herbicide, and many species are resistant to multiple herbicide classes. Regions that have practiced direct seeding over several decades have been particularly affected. As an example, weeds have become a major cause of yield decline for rice farmers in Sri Lanka who struggle to control grasses and sages using available products.

The chapter discusses the key components of integrated weed management (IWM), from preparation and control of the growing environment to establishing and managing the rice crop. Techniques which can be incorporated into an IWM strategy include choice of cultivar, tillage, crop rotation, water management, use of fertilizers and herbicides, as well as mechanical and biological control of weeds. Besides controlling existing weed problems, IWM puts greater emphasis on preventing weed reproduction and establishment in the first place, and on minimizing weed competition with the crop. Preventative techniques start with cultivar selection, measures to prevent seed contamination and appropriate land preparation techniques. As an example, some allelopathic rice cultivars can inhibit weed growth. Precision land levelling or using a laser levellers to create regular, sloping fields, for example, improves water management which can have a significant effect on both weed growth and bio-efficacy of herbicides. Scouting fields routinely and keeping non-cropped areas free of weeds can limit the persistence of weeds from one crop to the next.

Chapter 14 then covers establishment methods and planting patterns such as the use of stale seedbeds. Maintaining narrow row spacing and high seeding rates, for example, allows less space for weeds to become established. Some cultivation techniques such as conservation agriculture may promote the germination and emergence of weed seeds that stay on or near the soil surface. Herbicide application or mechanical weeding may be needed to eradicate these before sowing or planting. Cover crops like *Azolla* and mulches can also reduce weed problems in conservation agriculture by preventing weed seed germination or by suppressing the growth of emerging seedlings. Including crop rotation in conservation agriculture can also be a successful approach to reducing weed pressure. Well-targeted crop fertilization, especially nitrogen, is a promising agronomic practice in reducing weed interference in crops by helping crops to outperform weeds. However, under high weed pressure, crop fertilization can be counterproductive since nutrient absorption can be higher in weeds than in crop plants.

The chapter concludes by looking at mechanical and other methods for weed control. It covers developments in biological control such as *Hirschmanniella spinicaudata*, a rice root nematode which controls most upland rice weeds; *Bactra verutana,* a moth which destroys *Cyperus rotundu; Altica cyanea* (the steel blue beetle), which completely destroys *Ludwigia parviflora*; and the rust fungus *Puccinia canaliculata*, which controls *Cyperus esculentus* L. It then reviews the range of non-selective or selective, and pre-, early post- or post-emergence herbicides and ways they can best be deployed as part of an IWM programme.

Summary

Each chapter identifies potential avenues for further research. One common thread is the development of better monitoring techniques, whether to measure plant nutritional status, water losses from crops, pest or weed populations. The chapters in Volume 2 highlight a number of other common themes. They demonstrate the importance of the research community in understanding and explaining fundamental processes such as plant and pest ecosystems, and then using this understanding to design technologies and systems to ensure more resource-efficient, pest-free and sustainable rice cultivation.

However, as many chapters show, it is equally important then to translate these technologies and systems into practical programmes which farmers can use on the ground. This involves a range of processes such as localizing programmes so that they are tailored to local conditions, reducing costs so that technologies are affordable and translating programmes into a series of practical steps that farmers can implement easily. As Chapters 1, 10, 12 and 13 show, this also requires effective training and dissemination activities together with access to resources. As Chapter 8 demonstrates, farmers also need appropriate standards to work and the incentives to make improvements which may only benefit them in the long term.

A second major theme is the interconnectedness of many initiatives to improve rice cultivation, and potential synergies from integrating different approaches. One example is improving the efficiency of fertilizer management discussed in Chapter 2 which also has an impact on pest and weed management (as shown in Chapters 10, 12, 13 and 14). Chapter 3 provides an excellent example of the way different management practices can be combined to allow rice to be cultivated successfully and sustainably in a more challenging environment. Another aspect of such interconnectedness is how to navigate potential trade-offs between different programmes, for example reconciling aspects of conservation agriculture with effective weed management or rodent control. This links to a third common theme: the focus on conservation agricultural techniques. Anticipated to some degree by SRI, conservation agriculture, with its emphasis on understanding and optimizing soil health, has implications for improving water and nutrient management as well as control of insect pests.

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