IPM for tropical crops: rice

E. A. Heinrichs[1]* and Rangaswamy Muniappan[2]

Address: [1]IPM Innovation Lab, 6517 S. 19th St., Lincoln, NE, USA. [2]IPM Innovation Lab, OIRED, Virginia Tech, Blacksburg, VA, USA. ORCID.org: [1]http://orcid.org/0000-0003-0952-6052.

*__Correspondence__: E. A. Heinrichs. E-mail: eheinrichs2@unl.edu

Received: 6 April 2017
Accepted: 23 August 2017

doi: 10.1079/PAVSNNR201712030

The electronic version of this article is the definitive one. It is located here: http://www.cabi.org/cabreviews

Abstract

Rice is a staple food and the foundation of national stability and economic growth in many developing countries. Rice pests are major biotic constraints limiting rice production globally. This review discusses the biology, ecology, global distribution and plant damage and yield losses caused by insect pests, plant diseases, nematodes, rats and weeds. The interactions among insects, weeds and diseases are discussed. A proposed conceptual framework for arthropod pest management in organic crop production is explained. In this framework, arthropod pest management strategies are classified into four 'phases'. The framework prioritizes pest management options that will prevent damaging levels of pests (phase 1 and 2) and minimize the need for curative actions (phases 3 and 4). We adopt and modify this conceptual framework to structure a discussion on various rice pest management options in rice ecosystems. A detailed package of practices for managing rice pests is given. The relative efficiencies of the Farmers Field Schools and mass media campaigns in transferring IPM technology to rice farmers are discussed.

Keywords: Biological control, Cultural practices, Farmers field schools, Integrated pest management, IPM technology transfer, Mass media campaigns, Nematodes, *Oryza sativa*, Package of practices, Pest resurgence, Rice, Selective insecticides

Review Methodology: The following databases were searched for relevant articles from 1960 on: Agricola, CAB Abstracts and Google Scholar. This was supplemented by searching on the internet and through personal contacts.

Introduction

Rice, *Oryza sativa* L., – the staple food of an estimated 3.5 billion people worldwide [1] and the daily diet of nearly half the world's population – is the foundation of national stability and economic growth in many developing countries. It is also the primary source of income and employment for more than 200 million households across countries in the developing world [1].

Rice is currently grown on 163 million ha in over a hundred countries that produce more than 715 million tons (MT) of paddy rice annually (480 MT of milled rice) [2]. Fifteen countries account for 90% of the world's rice harvest China (197 MT of rough rice produced) and India (152 MT of rough rice produced) alone account for ~50% of the rice grown. Asian countries account for 90% of the world's total rice production. To feed the growing population an additional 116 Mt of rice will be needed by 2035 [3].

Rice cultivation has been the dominant land use in Asia for ages, but it is now playing an increasingly important role in Africa as well [1]. In West and Central Africa – the most impoverished regions on earth – rice is grown under subsistence conditions by about 20 million smallholder farmers who are shackled to slash-and-burn farming and who lack rice varieties that are appropriate to local conditions.

Rice Types and Cultivation

Rice is a semi-aquatic annual grass plant that includes approximately 22 species of the genus *Oryza*, of which 20 are wild [4]. Two species of rice are important for human consumption: *Oryza sativa* and *Oryza glaberrima*. *O. sativa* was first grown in Southeast Asia, somewhere in India, Myanmar, Thailand, North Vietnam, or China, between 8000 and 15 000 years ago. *O. glaberrima* is thought to have been domesticated from its wild ancestor *Oryza barthii* by people living in the floodplains of the Niger River in Africa about 3000 years ago [5]. Today, rice is cultivated on every continent except Antarctica. Of the two cultivated species, *O. sativa* is more widely grown, including in Asia, North and South America, the European Union, the Middle East and Africa. Cultivation of *O. glaberrima* is confined to Africa, where it is fast being replaced by *O. sativa* [1].

There are three basic types of rice production systems: *lowland*, *upland* and *deepwater*. *Lowland rice* is a method of rice production where rice is submerged for part or all of the growing season. Lowland rice production can be irrigated or rainfed and typically involves puddling of soil. With adequate irrigation water, two or even three crops of rice can be produced in a year. Availability and control of water helps reduce the risk of crop failure. As a result, farmers are willing to apply more purchased inputs like fertilizers typically resulting in higher yields. These and other factors help make the irrigated rice ecosystem the most productive http://www.knowledgebank.irri.org/submergedsoils/index.php/rice-growing-environments/lesson-2.

Upland rice is grown in rainfed fields prepared and seeded when dry, much like wheat or maize. Almost two-thirds of the upland rice area is in Asia. Bangladesh, Cambodia, China, India, Indonesia, Myanmar, Thailand and Vietnam are important producers [6].

Deepwater rice are varieties of rice (*Oryza sativa*) grown in flooded conditions with water more than 50 cm (20 in) deep for at least a month [7]. These varieties are grown in tropical monsoon climates normally around river deltas and their floodplains mainly in back swamps and natural levees. Floating rice grows in water deeper than 100 cm (39 in) through advanced elongation ability. The India cultivar is the main type of deepwater rice, although varieties of Japonica have been found in Burma, Bangladesh and India [7, 8].

Growth Phases of the Rice Plant

Rice plants take around 3–5 months to grow from seeds to mature plants, depending on the variety and environmental conditions. Growth of the rice plant is divided into three stages: (1). vegetative (germination to panicle initiation); (2) reproductive (panicle initiation to flowering); and (3) ripening (flowering to mature grain) (http://www.knowledgebank.irri.org/ericeproduction/0.2._Growth_stages_of_the_rice_plant.htm).

Some insects and diseases attack all stages of rice growth and others are specific as to which growth stage is attacked [9].

Rice Pests

To feed the growing world population, rice production must be increased. However, rice farmers face many abiotic and biotic constraints in their quest to increase rice production. In conjunction with the introduction of new high-yielding drought-and-flood-tolerant rice varieties, increasing yields will require a reduction in losses to insects and other stresses. As cropping intensity and cultural practices change, to meet production needs, pest pressure is expected to intensify.

Insects

All of the plant parts are vulnerable to insect – feeding from the time of sowing until harvest. There are over 800 insect species damaging rice in one way or another, although the majority of them do very little damage. According to Grist and Lever [10], in tropical Asia only about 20 species are of major importance and of regular occurrence. In Africa, 15 insect species are considered major pests of rice [11]) and in the Americas about 20 species are considered major pests [12] Insects are herein presented as based on feeding types.

1. Root and stem feeders,
2. Stem borers,
3. Rice gall midges,
4. Leafhoppers and planthoppers,
5. Foliage feeders and
6. Panicle feeders.

Root and stem feeders

Many insects feed on the roots and stems of rice plants (Table 1). Some, such as white grubs and root aphids, attack exclusively the roots; others (e.g. mealybug, rice stem maggot) infest only the stems, while still others, such as mole crickets, damage both roots and stems. The infestation of the rice crop, by different insect pests, is related to the growth stage of the plants [9]. Seedlings are prone to attack by pests such as rice seedling flies, rice seed midges and mole crickets. Insect damage at the early stages of crop growth causes seedling death and leads to an uneven stand.

The subterranean environment in which root-feeding insects live limits mobility, especially in locating food. For this reason root feeders have adapted by (1) being long-lived either as individuals (beetles), as colonies of social insects (termites), or as dependent on social insects (mealybugs and aphids) and (2) having a wide host range (all species) [13].

Root-feeding insects include the mole crickets (Orthoptera: Gryllotalpidae), tobacco cricket (Orthoptera: Gryllidae), root aphids (Hemiptera: Aphididae), mealybugs (Hemiptera: Pseudococcidae), black bugs, stink bug (Hemiptera: Pentatomidae), seed midges (Diptera: Chironomidae), stem maggot (Diptera: Chloropidae), seedling flies (Hemiptera: Muscidae), white grubs (Coleoptera: Scarabaeidae), grape colaspis (Coleoptera: Chrysomelidae), termites (Isoptera: Termitidae), root weevils, plant weevil, the rice water weevils (Coleoptera:

Table 1 Pests of rice and their geographical distribution – root and stem feeders

Insects	Asia	Africa	Europe	N. America	S. America	Australia
Root and stem feeders						
1. Mole crickets						
Gryllotalpa Africana (Orthoptera: Gryllotalpidae)		X				
2. Root aphids						
Tetraneura nigriabdominalis (Hemiptera: Aphididae)	X	X				
3. Rice root aphid						
Rhopalosiphum rufiabdominalis (Hemiptera: Aphididae)	X	X	X	X	X	X
4. Rice mealybug						
Brevennia rehi (Hemiptera: Pseudococcidae)	X					
5. Black bug						
Scotinophora lurida (Hemiptera: Pentatomidae)	X					
6. Black bug						
Scotinophora coarctata (Hemiptera: Pentatomidae)	X					
7. Rice stalk stink bug *Tibraca limbativentris* (Hemiptera: Pentatomidae)					X	
8. Chinch bug						
Blissus leucopterus (Hemiptera: Blissidae)				X		
9. Rice seed midges						
Cricotopus sylvestris, Paralauterborniella subcincta, and *Paratanytarsus* sp. (Diptera: Chironomidae)			X	X		
10. Rice stem maggot *Chlorops oryzae* (Diptera: Chloropidae)	X					
11. Rice seedling flies						
Atherigona exigua	X	X				
Atherigona oryzae (Diptera: Muscidae)	X	X				
12. Black beetles						
Heteronychus mosambicus (Coleoptera: Scarabeidae)		X				
13. ‘Chafers’ (white grubs)						
Leucophilus irrorata (Coleoptera: Scarabeidae)	X					
14. Colaspis beetles						
Colaspis brunnea				X		
Colaspis louisianae (Coleoptera: Chrysomelidae)				X		
15. Rice root weevil						
Echinocnemus oryzae (Coleoptera: Curculionidae)	X					
16. Rice plant weevil						
Echinocnemus squamous (Coleoptera: Curculionidae)	X					
17. Paddy Root Weevil						
Hydronomidius molitor (Coleoptera: Curculionidae)	X					
18. Rice water weevil						
Lissorhoptrus oryzophilus (Coleoptera: Curculionidae)	X		X	X	X	
19. Gorgulho aquatico						
Oryzophagus oryzae (Coleoptera: Curculionidae)					X	
20. Rice water weevil						
Afroryzophilus djibai (Coleoptera: Curculionidae)		X				
21. Subterranean termites						
Macrotermes bellicosus		X				
Pseudacanthotermes militaris		X				
Microtermis parvus		X				
Armitermes evuncifer		X				
Trinervitermes oeconomus		X				
Odontotermes obesus (Isoptera: Termitidae)	X					
22. Root-feeding termites						
Procornitermes triacifer					X	
P. araujoi					X	
Syntermes molestus (Isoptera: Termitidae)					X	

Curculionidae) and black beetles (Coleoptera: Scarabaeidae).

Stem borers

Rice stem borers (Table 2) are a key group of insect pests, mostly belonging to the two lepidopteran families of Pyralidae and Noctuidae. According to Pathak [14], pyralid borers are the most common and destructive of all stem borers and usually exhibit a high degree of host plant specificity. The noctuid borers, on the other hand, are polyphagous and only occasionally cause economic losses. In Asia, *Scirpophaga incertulas* and *Chilo suppressalis* are the

Table 2 Pests of rice and their geographical distribution – stem borers and gall midges

Insects	Asia	Africa	Europe	N. America	S. America	Australia
Stem borers and gall midges						
1. Stalk-eyed flies						
Diopsis longicornis		X				
D. apicalis (Diptera: Diopsidae)		X				
2. Gold-fringed rice borer						
Chilo auricilius (Lepidoptera: Crambidae)	X					
3. Dark-headed stem borer						
Chilo polychrysus (Lepidoptera: Crambidae)	X					
4. Spotted stem borer						
Chilo partellus (Lepidoptera: Crambidae)	X	X				
5. American rice stalk borer						
Chilo plejadellus (Lepidoptera: Crambidae)				X		
6 Rice striped borer						
Chilo suppressalis (Lepidoptera: Crambidae)	X		X			X
7. African striped rice borer						
Chilo zacconius (Lepidoptera: Crambidae)		X				
8. African white borer						
Maliarpha separatella (Lepidoptera: Pyralidae)		X				
9. Yellow stem borer						
Scirpophaga incertulas (Lepidoptera: Crambidae)	X					X
10. White stem borer						
Scirpophaga innotata (Lepidoptera: Crambidae)	X					X
11. African pink borer						
Sesamia calamistis (Lepidoptera: Noctuidae)		X				
12. West African pink borer						
Sesamia nonagrioides botanephaga (Lepidoptera: Noctuidae)	X	X				
13. Asiatic pink stem borer						
Sesamia inferens (Lepidoptera: Noctuidae)	X					
14. South American white borer						
Rupela albinella (Lepidoptera: Crambidae)					X	
15. Sugarcane borer						
Diatraea saccharalis (Lepidoptera: Crambidae)				X	X	
16. Lesser cornstalk borer						
Elasmopalpus lignosellus (Lepidoptera: Pyralidae)					X	
17. Mexican rice borer						
Eoreuma loftini (Lepidoptera: Pyralidae)				X		
18. Neotropical corn borer						
Diatraea lineolata (Lepidoptera: Crambidae)					X	
19. Asian rice gall midge						
Orseolia oryzae (Diptera: Cecidomyiidae)	X					
20. African rice gall midge						
Orseolia oryzivora (Diptera: Cecidomyiidae)		X				

major stem borers and are widely distributed from India to Japan. Although there is a number of species that feed on rice in West Africa, five are of major importance: the dipterous stalk-eyed flies (*Diopsis longicornis* and *Diopsis apicalis*) [15] and the lepidopterous species including the white stem borer (*Maliarpha separatella*), the striped stem borer (*Chilo zacconius*) and the pink stem borer (*Sesamia calamistis*) [16–19].

Various species of Lepidopteran stem-borers in the families Pyralidae, Noctuidae and Crambidae attack rice in North and South America. The most important stem-boring species are: *Diatraea saccharalis*, the sugarcane borer, which is the most widely distributed stem borer of rice in the New World and occurs from Argentina north to the southern United States; *Eoreuma loftini*, the Mexican rice borer, which is found in parts of northern Central America, Florida, and the western and southern United States; *Rupela albinella*, the white rice stem borer, found from Mexico to Brazil; *Elasmopalpus lignosellus*, the lesser cornstalk borer, a polyphagous insect, which is important as a rice pest in Mexico, Central and South America, especially in upland rice production systems. In Australia, rice is attacked by a species of *Phragmatiphila* [20].

Damage caused by the various lepidopterous stem-boring species is similar. Feeding by early instar stem borers on leaves and within leaf sheaths produces characteristic orange- tan lesions but is not economically damaging. Feeding within the culm on the growing point and vascular tissue can sever the growing portion of the plant from the base of the plant. When feeding occurs during the vegetative stage of plant development, the tiller in which the larva is present often dies and fails to produce a panicle (deadheart).

Rice is capable of partly or fully compensating for losses of tillers from stem borer attack of vegetative-stage rice by putting forth additional tillers [21]. When feeding occurs after panicle initiation, feeding by a larva within a stem results in drying of the panicle. Affected panicles may not emerge or, if they do, do not produce grains, remain straight and appear whitish (whitehead).

Infestations in rice fields often involve multiple species of borers, and yield losses under severe infestations can reach as high as 60% [21]. For every percent of white head, 1–3% loss in yield may be expected [22]. However, yield losses from stem borers have not been adequately characterized.

Rice gall midges

Globally, there are two major, closely related rice gall midge species attacking rice, the Asian species *Orseolia oryzae* and the African species *Orseolia oryzivora* [23] (Table 2). Both midge species are primarily pests of lowland irrigated rice. In addition, the damage caused by the two species is similar. The main external symptom of attack is a 'silver shoot' or a 'gall' that resembles an onion leaf. The gall, which produces no grain, forms instead of the development of a panicle [12].

Leafhoppers and planthoppers

The leafhopper (Cicadellidae) and planthopper (Delphacidae) genera occurring in Asia are also present in West Africa, but the species are different (Table 3). The West African species are similar in appearance to Asian species but they are of only minor importance. In Asia, their importance has escalated with the intensification of rice production, especially the misuse of insecticides. Both African and Asian species not only cause direct plant damage, by removing the sap from leaves and stems, but several are also efficient vectors of rice viruses [24, 25]. Leafhoppers attack all aerial parts of the plant but planthoppers occur primarily on the basal portion of the plant [25].

The brown planthopper, *Nilaparvata lugens*, however, is a serious pest because it causes direct damage through the removal of large amounts of plant sap, and is a vector of several serious rice viruses [26–28]. In Asia, the sudden increase in the importance of these pests in the 1970s was attributed to the changes in cultural practices accompanying the intensification of rice production during the Green Revolution. It appears that high levels of nitrogen fertilizer, monocultures, continuous cropping and mainly the application of insecticides that cause hopper resurgence are some of the intensification practices contributing to leafhopper and planthopper outbreaks [27, 29]. In West Africa, the hoppers are still considered as only potential pests, which should be closely monitored as production practices are intensified.

Tagosodes cubanus, a pest of rice in South and Central America, is a vector of the rice hoja blanca virus, which can cause up to 50% yield loss [30]. The rice delphacid *Tagosodes oryzicolus* is a serious pest in tropical Central American, Caribbean and South American rice-growing countries where it causes direct damage and transmits hoja blanca virus [31]. This insect migrates and has occasionally been found (but not established) as far north as Texas and Louisiana, and as far south as Argentina.

Nisia nervosa is the only member of the Meenoplidae family attacking rice. The preferred host plant appears to be a sedge species, Cyperaceae [32, 33], but rice is frequently used as a host [34]. Grist and Lever [10] mention it as a minor pest of rice, and Huang and Qi [35] have recorded it on rice and sugarcane in China.

Locris spp. (Cercopidae) are confined to Africa and can transmit Rice Yellow Mottle Virus (RYMV) [36]. They are easily recognized by their large size and red, orange, or brown coloration and patterning of the fore wings and head. Little is known about the biology of *Locris* spp. Akingbohungbe [37] records *Locris rubens*, *Locris maculata maculata*, and *Locris rubra* as minor pests of cereals in Nigeria. The most common *Locris* spp. occurring on rice are *Locris erythromela*, *L. maculata maculata*, *L. rubra*, and *L. rubens* (Akinsola, WARDA, 1992, pers. commun.). They prefer irrigated and lowland rice to upland rice. Severe plant damage caused by *Locris* spp. is not common but leaf bronzing and wilting can occur.

Nephotettix spp. are severe pests of rice in Asia, where *Nephotettix virescens*, *Nephotettix cincticeps* and *Nephotettix nigropictus* are vectors of the virus diseases tungro, rice transitory yellowing, rice dwarf virus, rice gall dwarf and yellow dwarf. In West Africa, *N. afar*, so far, is of only minor importance, and populations seldom reach levels where feeding injury causes economic damage to rice and it is not known to be a virus vector. *Nephotettix modulatus,* however, has recently been reported to be a vector of RYMV in Africa [36].

Two other cicadellid species, *Cofana spectra* and *Cofana unimaculata* occur on rice in West Africa. Both are widely distributed in the Old World tropics from Africa to Australia. Recent studies by Koudamiloro *et al.* [36] and Nwilene *et al.* [38] have shown that *Cofana spectra* and *C. unimaculata* are RYMV vectors in Africa.

Several cicadellid species of the genus *Recilia* are found on rice throughout the world. Of these, the zigzagged leafhopper, *Recilia dorsalis*, is an important rice pest in Asia where it transmits tungro, rice dwarf, rice gall dwarf and orange leaf viruses [34]. *Recilia mica* has only been recorded from West Africa [39], where it has been reported on rice [40], but evidence of crop damage has not been reported.

Foliage feeders

The 'foliage feeders' refers to a broad category which consists of a number of insect orders including the Hemiptera, Thysanoptera, Lepidoptera, Diptera, Coleoptera, Orthoptera (grasshoppers) and mites that feed on rice foliage [12] (Table 4). The group has mouthparts which determine the type of feeding damage caused. The lepidopterous larvae, coleopterous larvae and

Table 3 Pests of rice and their geographical distribution – leafhoppers and planthoppers

Insects	Asia	Africa	Europe	N. America	S. America	Australia
Leafhoppers and planthoppers						
1. White rice leafhoppers						
Cofana spectra	X	X				X
C. unimaculata (Hemiptera: Cicadellidae)	X	X				X
2. Green leafhoppers						
Nephotettix nigropictus	X					X
N. afer		X				
N. virescens	X					
N. cincticeps	X					
N. malayanus	X					
N. parvus	X					
N. modulatus (Hemiptera: Cicadellidae)	X	X				
3. Zigzag leafhopper						
Recilia dorsalis (Hemiptera: Cicadellidae)	X					X
4. Smaller brown planthopper						
Laodelphax striatellus (Hemiptera: Delphacidae)	X	X	X			
5. Brown planthopper (Asian)						
Nilaparvata lugens (Hemiptera: Delphacidae)	X					X
6. Brown planthopper (African)						
Nilaparvata maeander (Hemiptera: Delphacidae)		X				
7. Whitebacked planthopper						
Sogatella furcifera (Hemiptera: Delphacidae)	X					X
8. Rice delphacids						
Tagosodes orizicolus		X			X	
T. cubanus (Hemiptera: Delphacidae)					X	
9. Spittlebugs						
Locris maculata maculata		X				
L. rubra (Hemiptera: Cercopidae)		X				
10. Spittlebug (Cigarrinha das pastagens)						
Deois flavopicta (Hemiptera: Cercopidae)					X	

adults and orthopteran nymphs and adults, have chewing mouthparts, which are used to defoliate plants.

The Whitefly, *Aleurocybotus indicus* (Hemiptera: Aleyrodidae) damages plants by sucking sap from the leaves. Honeydew, which is excreted on the leaves by the feeding of nymphs and adults, has a high sugar content and a black sooty mould fungus grows on it. Extensive feeding and high amounts of sooty mould may eventually lead to wilting and death of the plants [41].

Spider mites, *Oligonychus pratensis*, *Oligonychus senegalensis*, *O. oryzae and Tetranychus neocaledonicus* (Acari: Tetranychidae) suck sap from the leaves and produce large masses of webbing. Leaves become discoloured with white patches and dry up, starting from the leaf tip. Plants become stunted with deformed panicles and empty spikelets [24].

Rice thrips, *Stenchaetothrips biformis* (Thysanoptera: Thripidae) larvae and adults have rasping-sucking mouthparts that lacerate the green tissue of leaves. Young plants, usually of 1–2 weeks after transplanting, are the most affected. Damage becomes evident as fine yellowish lines or silvery streaks on the leaves, which later curl from the margin towards the midrib. In severe infestations, the plants become stunted and wither [25].

The major rice leaffolder species are *Cnaphalocrocis medinalis*, *Marasmia patnalis*, *Marasmia ruralis* and *Susumia exigua* (Lepidoptera: Pyralidae). Leaffolder larvae fold the rice leaves by spinning silk from one edge of the leaf to the other, and as the silk shrinks, the leaf folds. Then the larvae feed on the green tissues of the leaf from within the fold. Feeding damage causes the leaf to dry, which severely restricts photosynthetic activity of the plant [24].

The green-horned caterpillar, *Melanitis leda ismene* (Lepidoptera: Satyridae), is among a number of defoliating insects that are minor feeders on rice in Africa and Asia [42, 43]. The pest occurs in all environments, but is most prevalent in rainfed rice. The larva feeds on the margins and tips of leaves and removes leaf tissue and veins. Damage is similar to that made by grasshoppers and armyworms [24].

The larvae of the rice ear-cutting caterpillar, *Mythimna separata*, fall armyworm, *Spodoptera frugiperda*, rice swarming caterpillar, *Spodoptera mauritia, and the* common armyworm, *Mythimna unipuncta* (Lepidoptera: Noctuidae), are voracious feeders removing large areas of leaf blade or entire leaves and even completely stripping the plants. When large numbers are present, entire seedlings can be defoliated, resulting in severe stand loss [25, 44].

Larvae of the rice whorl, *Hydrellia prosternalis* and *Hydrellia philippina* (Diptera: Ephydridae), feed on the mesophyll tissues within the leaf whorl. When the leaves emerge from the whorl, damage can be seen as pinholes in the leaves, which show white and yellowish lesions at the leaf edges. Severely damaged leaves break in the wind [25].

Table 4 Pests of rice and their geographical distribution – foliage feeders

Insects	Asia	Africa	Europe	N. America	S. America	Australia
Foliage feeders						
1. Large rice grasshoppers						
Hieroglyphus banian	X					
H. nigrorepletus (Orthoptera: Acrididae)	X					
2. Rice grasshopper						
Hieroglyphus daganensis (Orthoptera: Acrididae)		X				
3. Short-horned grasshopper						
Oxya hyla	X	X				
O. chinensis	X	X				
O. velox	X	X				
Oxya hyla intricata	X	X				
O. japonica japonica (Orthoptera: Acrididae)	X					
4. Variegated grasshopper						
Zonocerus variegatus (Orthoptera: Acrididae)		X				
5. Meadow grasshoppers						
Conocephalus maculates	X	X				X
Conocephalus longipennis (Orthoptera: Tettigoniidae)	X	X				X
6. Whitefly						
Aleurocybotus indicus (Hemiptera: Aleyrodidae)	X	X				
7. Rice whitefly						
Aleurocybotus occiduus (Hemiptera: Aleyrodidae)	X			X	X	
8. Spider mites						
Oligonychus pratensis		X		X	X	
O. senegalensis		X				
O. oryzae	X					
Tetranychus neocaledonicus (Acarina: Tetranychidae)	X	X				
9. Rice thrips						
Stenchaetothrips biformis (Thysanoptera: Thripidae)	X		X		X	
10. Rice leaffolder						
Cnaphalocrocis medinalis (Lepidoptera: Crambidae)	X					
11. Rice leaffolder						
Marasmia patnalis (Lepidoptera: Crambidae)	X					
12. Fijian rice leaffolder						
Susumia exigua (Lepidoptera: Pyralidae)	X					X
13. Rice caseworm						
Nymphula depunctalis (Lepidoptera: Crambidae)	X	X			X	
14. Green horned caterpillar						
Melanitis leda ismene (Lepidoptera: Nymphalidae)	X	X				X
15. Rice skippers						
Parnara guttata	X					
Pelopidas mathias (Lepidoptera: Hesperidae)	X	X				
16. Rice ear-cutting caterpillar						
Mythimna separata (Lepidoptera: Noctuidae)	X		X			X
17. Fall armyworm						
Spodoptera frujiperda (Lepidoptera: Noctuidae)				X	X	
18. Common cutworm						
Spodoptera litura (Lepidoptera: Noctuidae)	X					X
19. Rice swarming caterpillar						
Spodoptera mauritia (Lepidoptera: Noctuidae)	X	X				X
20. Common armyworm						
Mythimna unipuncta (Lepidoptera: Noctuidae)		X	X	X	X	
21. Rice green semilooper						
Naranga aenescens	X					
N. diffusa (Lepidoptera: Noctuidae)	X					
22. Green hairy caterpillar						
Rivula atimeta (Lepidoptera: Noctuidae)	X					
23. Rice whorl maggots						
Hydrellia philippina	X					
H. prosternalis (Diptera: Ephydridae)		X				
24. Rice leaf miner						
Hydrellia griseola (Diptera: Ephydridae)	X		X	X	X	
25. South American rice miner						
Hydrellia wirthi (Diptera: Ephydridae)				X	X	

Table 4 (Continued)

Insects	Asia	Africa	Europe	N. America	S. America	Australia
26. Paddy stem maggot						
Hydrellia sasakii (Diptera: Ephydridae)	X					
27. Asian rice hispa						
Dicladispa armigera (Coleoptera: Chrysomelidae)	X					
28. *African rice hispa*						
Trichispa sericea (Coleoptera: Chrysomelidae)		X				
29. *Rice blue beetle*						
Leptispa pygmaea (Coleoptera: Chrysomelidae)	X					
30. Rice leaf beetle						
Oulema oryzae (Coleoptera: Chrysomelidae)	X					
31. Flea beetles						
Chaetocnema pulla		X				
C. pusilla (Coleoptera: Chrysomelidae)		X				
32. Ladybird beetle						
Chnootriba similis (Coleoptera: Coccinellidae)		X				
33. Leaf miner						
Cerodontha orbitona (Diptera: Agromyzidae)		X				
34. Foliage feeding aphids						
Aphis craccivora	X	X	X	X	X	X
Aphis gossyppi	X	X	X	X	X	X
Brachysiphoniella montana	X					
Diuraphis noocia		X				
Hysteroneura setariae	X	X				
Melanaphis sacchari	X					
Metopolophium dirhodum	X					
Myzus persicae	X	X	X	X	X	X
Rhopalosiphum maidis	X	X	X	X	X	X
Rhopalosiphum nymphaeae	X		X	X		
Rhopalosiphum padi	X	X	X	X	X	X
Schizaphis graminum	X	X		X	X	
Sipha glyceriae			X			
Sitobion akebiae	X					
S. avenue	X		X	X		
S. fragariae			X			
S. miscanthi (Hemiptera: Aphididae)	X					

Several species belonging to the Coleoptera – Chrysomelidae, subfamily Hispinae, feed on rice in Africa and Asia. Both grubs and adult beetles feed on rice plants. Grubs mine the leaves by feeding on the mesophyll between the veins. Adults feed on the leaf surfaces, giving the appearance of white parallel streaks and white irregular blotches on the leaves. Some African hispids are vectors of RYMV [24, 25].

Flea beetles (Coleoptera: Chrysomelidae) make small holes in the leaf when feeding. Although *Chaetocnema* spp. are extremely abundant in upland rice, in West Africa, the feeding damage that they cause is minimal. However, they are vectors of RYMV [24, 45].

Many aphid species (Hemiptera: Aphididae) infest the aerial parts of rice even though rice is not the primary host plant for most of them [25]. The rusty plum aphid *Hysteroneura setariae* is a pest on rice leaves in Africa and Asia. *Rhopalosiphum padi*, known as the bird cherry oat aphid and grain aphid, is a foliage feeder with worldwide distribution (Table 4). It is a vector of the virus disease 'giallume' (yellow disease or rice yellows) in Italy, where its primary host is the fruit tree *Prunus padus* [25]. A number of species of grasshoppers are occasionally found in rice fields, but rarely cause significant damage other than along the field margins.

Nearly 30 grasshopper species, belonging to the short-horned (Acrididae and Pyrgomorphidae) and the long-horned (Tettigoniidae) families, attack rice plants in West Africa. However, most species are not of economic importance on rice because they occur in low populations.

Panicle feeders

Insects that attack rice panicles can be separated into those that feed on the floral parts (mostly the pollen) and the stink bugs that suck the milk-like sap from the developing grains. Insects that feed on the floral parts, such as earwigs, blister beetles and panicle thrips prevent the spikelet from filling and thus it remains empty and aborts.

Numerous hemipteran insect species that suck the milk from developing grains belong to the Alydidae, Coreidae, Pentatomidae and Pyrrhocoridae families and are considered rice bugs. The rice bugs most commonly found in rice in Asia are the alydids *Leptocorisa acuta*, *Leptocorisa chinensis*, *Leptocorisa varicornis* and *Leptocorisa oratorius*. The pentatomid *Nezara viridula* is found in all geographical regions (Table 5). Several *Oebalus* species are panicle

Table 5 Pests of rice and their geographical distribution – panicle feeders

Insects	Asia	Africa	Europe	N. America	S. America	Australia
Panicle feeders						
1. (Hemiptera: Alydidae)						
Leptocorisa acuta	X				X	X
L. chinensis	X					
L. varicornis	X					
L. oratorius	X					X
Mirperus jaculus		X				
Riptortus dentipes		X				
Stenocoris apicalis		X				
S. claviformis		X				
S. elegans		X				
2. (Hemiptera: Coreidae)						
Cletus punctiger	X					
3. (Hemiptera: Lygaeidae)						
Nysius plebejus	X					
Togo hemipterus	X					
4. (Hemiptera: Miridae)						
Stenodema sibiricum	X					
Trigonotylus coelestialium	X					
5. (Hemiptera: Pentatomidae)						
Aspavia armigera		X				
A. acuminata		X				
A. brunnea		X				
Dolycoris baccanum	X					
Eysarcoris lewisi	X					
E. parvus	X					
E. ventralis	X					
Lagynotomus elongatus	X					
Nezara viridula	X	X	X	X	X	X
Oebalus pugnax				X		
O. poecilus					X	
O. ypsilongresius				X	X	
O. insularis				X	X	
O. ornata					X	
Scotinophara lurida	X				X	
6. (Hemiptera: Rhopalidae)						
Aeschynteles maculatus	X					
7. Blister beetles (Coleoptera: Meloidae)						
Cylindrothorax melanocephala		X				
C. spurcaticollis		X				
C. westermanni		X				
Epicauta canescens		X		X		
E. funebris						
Mylabris sp		X				
8. Panicle thrips (Thysanoptera: Phlaeothripidae)						
Haplothrips ganglbaueri	X					
H. avenae		X				
H. gowdeyi	X	X		X	X	X
9. Panicle mites (Acarina: Tarsoemidae)						
Steneotarsonemus spinki	X			X	X	

feeders in North and South America. Blister beetles species of the genus *Cylindrothorax* are panicle feeders in Africa [12].

Rice diseases

Rice diseases are major constraints to rice production in all rice producing regions of the world. Some diseases occur worldwide and others are specific to a given region. Various agents acting singly or in combination cause plant diseases. The agents can be biotic (living) or abiotic (nonliving). Living, disease-inciting organisms are called pathogens. The pathogens of rice diseases are fungi, bacteria, nematodes, viruses and mycoplasma-like organisms. These pathogens cause visible disease symptoms on the entire plant, or on individual plant parts such as roots, stems, leaves, leaf sheaths, panicles or grains [9].

Fungi

The geographical distribution of the major rice fungal diseases is given in Table 6. Several are widely distributed in all the six rice producing regions. Of these, rice blast *Magnaporthe oryzae,* is one of the most serious rice diseases because it infects all plant growth stages, it spreads rapidly and is highly destructive. Apparently, recorded in China in 1637 and Japan in 1704, it is considered the earliest known and most widespread disease of rice [46].

Blast attacks all parts of the rice plant except the leaf sheath. Depending on the site of the symptoms, blast is referred to as leaf last, collar blast, node blast and neck blast ('neck rot'). Leaf blast not only stunts or kills seedlings and tillering plants. It also reduces the number of panicles and lowers grain weight and quality. A 10% infection of neck blast causes a 6% yield loss and a 5% increase in chalky kernels. Panicle blast causes more severe losses. Collar blast can also kill the entire leaf blade. With severe infection, the panicle neck may be girdled by a greyish-brown lesion causing the panicle to fall over.

Bacteria

According to Islam and Catling [46] bacterial blight is the most severe bacterial disease of rice. It occurs in all regions except Europe (Table 6).

Bacterial blight is a vascular disease, bacteria moving along the conducting tissues to cause a wilting of the whole plant. Bacterial cells ooze from young lesions in the presence of dew and rain. Drops of water containing bacterial cells then dry to form minute, yellowish, spherical beads that are blown by the wind and fall into the paddy water.

Bacterial blight infecting the plant from maximum tillering to the booting stage causes poorly developed grains and reduced grain weight. In India, Indonesia and other tropical countries the severe '*kresek form*' of the disease often kills young plants; the earlier the attack the greater the damage [47]. The most important source of kresek infection is diseased stubble. The pathogen readily survives on crop residues of stubbles and ratoons and high bacterial populations are found in irrigation water, along canals and in rice fields. Bacteria spread from one plant or field to another through irrigation water, wind and by plant-to-plant contact. The disease usually starts in small patches and then gradually spreads to other parts of the field until the whole field is infected.

Viruses

Virus diseases have been considered to be of minor importance worldwide being estimated to cause average annual crop losses of <1.5% [27]. However, sporadic epidemics of rice virus diseases can cause severe grain yield losses in a given country or region [48]. For instance, the areas where tungro virus is epidemic are few in relation to the total rice production of the region or country, but affected fields may suffer a total yield loss. Such devastating damage has a significant impact on the livelihood of farmers in Asia, who generally depend on the crops produced on the generally small farms [49].

The major rice viruses and their geographical distribution are listed in Table 6. The most economically important viruses in Asia are rice tungro, vectored by the green leafhoppers *Nephotettix* spp. and rice grassy stunt is vectored by the brown planthopper *Nilaparvata lugens.* Hoja blanca, vectored by the planthoppers *Tagosodes oryzicolus* and *Tagosodes cubanus* is the sole virus attacking rice in Central and South America. RYMV, the only known rice virus in Africa, is mechanically transmitted by leafhoppers, spittle bugs, a number of foliage feeding beetles and grasshoppers and any animal movement within the field including farm workers. Rice giallume (yellow virosis), transmitted by the Bird cherry-oat aphid *Rhopalosiphum padi* is an important virus disease of rice in Italy.

Tungro virus. *Rice Tungro Spherical Virus (RTSV)* is one of the most damaging and destructive diseases of rice in South and Southeast Asia [46]. In severe cases, tungro susceptible varieties infected at an early growth stage could have as high as 100% yield loss. Two distinct virus particles, rice tungro bacilliform virus (RTBV) and RTSV, cause the rice tungro disease [50]. Disease symptoms depend on whether one or both viruses are present on the plant (Table 6). Tungro causes leaf discoloration, deformed leaves, stunted growth, reduced tiller numbers and sterile or partly filled grains.

Tungro disease viruses are transmitted from one plant to another by leafhoppers, *Nephotettix virescens*, *Nephotettix cincticeps*, *Nephotettix malayanus* and *Nephotettix parvus.* The most efficient vector is the green leafhopper *N. virescens*. Among the diseases transmitted by *Nephotettix* virescens (tungro, leaf yellowing, transitory yellow dwarf, orange leaf), tungro is the most destructive. The infection occurs primarily in the early stages of crop growth. It is the only known non-persistent or transitory rice virus [51]. When the epidemic is severe, 100% yield loss can occur [26]. Tungro virus has become increasingly important since the mid-1960s; major outbreaks occurred in 1969 and thereafter repeatedly in many countries including Indonesia, Thailand, Malaysia, Bangladesh and India [52].

Grassy stunt virus. *Grassy Stunt Virus (RGSV)* has caused severe damage, in sporadic outbreaks in limited areas, but is generally not considered a widespread problem [9]. The BPH, one of the most damaging insect pests in Asian rice, transmits the viruses *RGSV* and *Rice Ragged Stunt Virus* (*RRSV*) [27, 52–54].

RGSV occurs in most of Asia (Table 6). Rice is the preferred host but *RGSV* also develops on many species of wild rice [9]. *RGSV* affects rice crops in areas where continuous, year-round rice growing is practised. The interaction between virus and vector is persistent and there is no transovarial passage. *RGSV* is not transmitted through rice seed [46].

Table 6 Diseases of rice and their geographical distribution – fungal, bacterial, viral and nematode diseases

Diseases	Asia	Africa	Europe	N. America	S. America	Australia
Fungal diseases						
Rice blast						
Magnaporthe oryzae	X	X	X	X	X	X
Sheath blight						
Rhizoctonia solani	X	X	X	X	X	X
Sheath rot						
Sarocladium oryzae	X	X		X	X	X
Stem rot						
Helminthsporium sigmoideum	X	X	X	X	X	X
Stem rot						
Sclerotioum oryzae	X	X	X	X	X	X
False smut						
Ustilagnoidea virens	X	X	X	X	X	X
Brown spot						
Bipolaris oryzae	X	X	X	X	X	X
Leaf scald						
Microdochium oryzae	X	X		X	X	X
Narrow brown leaf spot						
Cercospora janseana	X	X		X	X	X
Bakanae						
Gibberella fujikuroi	X	X	X	X	X	X
Bacterial diseases						
Bacterial blight						
Xanthomonas oryzae pv. *oryzae*	X	X		X	X	X
Bacterial leaf streak						
Xanthomonas oryzae pv. *oryzicola*	X	X				X
Grain rot						
Burkholderia glumae	X	X		X	X	
Sheath brown rot						
Pseudomonas fuscovaginae	X	X			X	X
Viral diseases						
Rice black-streaked dwarf	X					
Rice bunchy stunt	X					
Rice dwarf	X					
Rice gall dwarf	X					
Rice yellow dwarf	X					
Rice giallume			X			
Rice grassy stunt	X					
Rice ragged stunt	X					
Rice hoja blanca				X	X	
Rice necrosis mosaic	X					
Rice stripe necrosis	X					
Rice stripe	X					
Rice stripe necrosis benyvirus		X			X	
Rice transitory yellowing	X					
Rice tungro bacilliform	X					
Rice tungro spherical	X					
Rice yellow mottle		X				
Rice orange leaf virus	X					
Rice crinkle disease		X				
Maize streak geminivirus strain A		X				
African cereal streak virus		X				
Rice waika machlovirus	X					
Nematode diseases						
Ufra or stem nematode						
Ditylenchus angustus (Nematoda: Anguinidae)	X					
White tip nematode						
Aphelenchoides besseyi (Nematoda: Aphelenchoididae)	X	X	X	X	X	X
Root-knot nematode						
Meloidogyne graminicola (Nematoda: Meloidogynidae	X	X		X	x	
Rice root nematode						
Hirschmanniella oryzae (Nematoda: Pratylenchidae)	X	X	X	X	X	
Rice cyst nematode						
Heterodera oryzicola (Nematoda: Heteroderidae)	X					

Hoja blanca. The delphacid transmitted *Rice hoja blanca virus* (*RHBV*) is a member of the genus Tenuivirus, a plant virus genus [55]. The disease is found throughout South and Central America and the Caribbean region. In South America (Table 6) the disease is endemic to Colombia, Venezuela, Ecuador, Peru, Suriname, French Guiana and Guyana [31].

The delphacid planthoppers *Tagosodes orizicolus* and *Tagosodes cubanus* (Table 3) both cause indirect damage known as 'hopperburn' and indirect damage through the transmission of RHBV [56].

The RHBV symptoms in rice are chlorotic streaks that can coalesce and cause the leaves to turn white. When young plants become infected, they are stunted and in severe cases the leaves turn necrotic and the plants die. Besides its notable spatial dissemination capacity, the main concern of rice growers and agricultural scientists in South and Central America was the significant yield losses that this disease could induce in susceptible rice cultivars, as a result of seedling death, reduced photosynthetic capacity, plant dwarfing and panicle sterility [57–59].

Yellow mottle. *Rice Yellow Mottle Virus* (*RYMV*) is the major viral constraint to rice production in Sub-Saharan Africa. RYMV infects cultivated and wild grasses belonging to Oryzae and Eragrostidae tribes. Yield losses vary widely, from 10 to 100% depending on the type of variety and period of infection. Early infection normally leads to higher losses. According to Koudamiloro *et al.* [36] RYMV was first identified in 1966 in Kenya and then later in most African countries where rice is grown. RYMV was first reported on rice in West Africa in 1976. In lowland irrigated rice and in mangrove and inland swamps in Guinea RYMV was first observed during the period 1982–86 [60], and in upland rice in Cote d'Ivoire in 1985 and Sierra Leone during 1987 [61]. RYMV is endemic and largely restricted to the African continent, where it has been found in most of the rice-growing countries.

Both sucking insects and foliage feeders, with mandibular mouthparts, mechanically transmit RYMV. In addition, any organism moving through the field rubbing against the leaves of rice plant including, rats, birds, farm workers etc. can mechanically transmit RYMV. RYMV can also be mechanically transmitted through inter-plant movement of sap (irrigation water, guttation water and contact between infected and healthy plant tissues and crop residues). Rice plants, alternate hosts, ratoon or stubbles that grow between cropping seasons, allow the continuous survival of the pathogen.

Numerous foliage feeding insects have been reported to mechanically transmit RYMV. According to IRRI [62], Reckhaus and Andriamasintseheno [63] and Koudamiloro *et al.* [36, 64], the short-horned grasshopper *Oxya hyla* (Table 4) transmits RYMV.

RYMV symptoms initially appear as yellow-green oblong to linear chlorotic mottles spots on the base of the youngest leaves, chlorotic mottles later expand parallel to the leaf veins and coalesce into broken or continuous pale green to yellowish or orange streaks up to 10 cm long. Later, whole plants become light green and then turn to pale yellow. Leaves formed after infection are often twisted. Symptoms of the virus disease are pale yellow mottled leaves, stunted growth, reduced tillering, asynchronous flowering, poor panicle exsertion, spikelet discoloration and sterility. From a distance, infected fields appear yellow [24]. Severely infected plants eventually die.

Giallume. The disease was first observed in Italy (Table 6) in 1955 and it has become more common thereafter [65]. The disease *Rice Giallume* is a strain of '*Barley Yellow Dwarf Virus*' (BYDV). In Italy, it is transmitted most efficiently by the bird cherry oat aphid, *Rhopalosiphum padi,* but can also be transmitted by the aphids *Sitobion avenae* and *Metopolophium dirhodum.* The virus is introduced into a new crop by alate aphids from infected weeds e.g. *Leersia oryzoides* (primary infection). Secondary spread within the field depends on weather conditions favourable to aphid development and spread <http://www.cabi.org/isc/datasheet/10539>.

Nematode diseases

Plant-parasitic nematodes are recognized as one of the greatest threat to crops throughout the world. Nematodes alone or in combination with other soil microorganisms have been found to attack almost every part of the plant including roots, stems, leaves, fruits and seeds [66]. Some of the rice nematodes of economical importance are the ufra or rice stem nematode (*Ditylenchus angustus*); white tip nematode (*Aphelenchoides besseyi*); the root-knot nematode (RRN; *Meloidogyne graminicola)* [67], the RRN (*Hirschmanniella oryzae*) and the rice cyst nematode (*Heterodera oryzae*) (Table 6).

Ufra disease, caused by the stem nematode, *Ditylenchus angustus* (Table 6) is a major disease of deep water and lowland rice in parts of Asia [68] and is regarded as the fourth worst disease of rice in Bangladesh according to Islam and Catling [46] 2012). Yield losses induced by this nematode are serious and range from 20 to 90% [69].

The stem nematode is mostly confined to deeply flooded cultivated rice, particularly deepwater rice and the *Oryza* wild rices. It has also been reported on grassy weeds including *Echinochloa colona* and *Leersia hexandra.* It develops and reproduces in the leaf sheath and stalk, where it feeds ectoparasitically on meristematic tissues [70]. Ufra disease is characterized by first whitish and then brownish leaf tips, stem distortion above the last node and arrested development of the ear, and in heavily attacked plants, by decay. The nematodes are spread by rain splash and irrigation water.

The primary source of inoculum at the start of the season is crop residues left in the field, many stems containing several hundred nematodes. At first, the numbers decrease, as infested stems are drowned by rising food water. Nematodes then disperse in the water to form a secondary infestation over an 18-week period. Finally, tertiary infestations develop from water-borne inoculum that produce the typical ufra patches. With plant senescence, the nematodes cease to feed, coil up and enter a resting condition at the base of the peduncle and in glumes in order to survive the dry season [46].

White tip. White tip is caused by the nematode, *Aphelenchoides besseyi*. It is seed borne and occurs in many rice-growing areas throughout the world including tropical and temperate countries (Table 6). First reported in Japan in 1915 it was only in 1948 that the cause of the disease was attributed to a nematode [46].

The white tip disease is usually more serious in temperate regions than in the tropics. The white tip nematode is by far the most common species associated with cultivated irrigated lowland rice in Louisiana (USA) http://www.lsuagcenter.com/profiles/coverstreet/articles/page1461341714090.

The most characteristic symptom is a dark green leaf with a white, chlorotic tip of up to 5 cm in length. Infected leaves are darker green than the normal. The flag leaves of severely damaged plants may be twisted and panicles from the boot may not emerge or are sterile from distorted glumes and small, misshapen kernels. The hulls and kernels may be small and deformed. Rice seed, infected with the white tip nematode, is the primary method of spread.

Root knot nematode. The root knot nematode, *Meloidogyne graminicola*, is an obligate sedentary endoparasite adapted to flooded conditions. It is found in both upland (rainfed) and lowland (irrigated) rice, as well as in deepwater ecosystems [71]. It is a pest of rice in Asia, Africa, North and South America (Table 6).

M. graminicola is a true root nematode forming characteristic knots or galls on the root tips of rice seedlings, which retard or arrest the growth of root tips [46]. Losses in flooded rice fields occur by drowning of plants when infected seedlings fail to elongate above the rising floodwater, leaving patches of open water in flooded fields [72]. Under simulated upland or intermittently flooded conditions, yield losses caused by the root knot nematode range from 20 to 80% and 11 to 73%, respectively [73, 74]. In the field, these losses may be exacerbated in combination with other biotic or abiotic stresses, such as drought.

Rice root nematode. *Hirschmanniella oryzae*, the RRN, is among the major pests of rice and is the most common plant-parasitic nematode found on irrigated rice [75]. Except for Australia, RRN can be found throughout rice- and non-rice-growing regions of the world, including the USA (Table 6), but is most commonly found in tropical and subtropical regions of Asia.

Rice cyst nematode. Four species of infect rice. *Heterodera oryzicola* and *Heterodera elachista* are found on upland rice only in Kerala, India and Japan respectively, while *H. oryzae* and *Heterodera sacchari* are more widespread, occurring on upland and lowland rice, principally in West Africa [69] (Table 6). Banana is also a host for *H. oryzae* [76] and *H. oryzicola* [77].

Individual females of *H. oryzicola*, *H. elachista* and *H. oryzae* deposit many eggs into a large egg sac from which the juveniles hatch freely in water. Evidence suggests that juveniles in eggs retained in the cysts require host root diffusates to stimulate hatch [78]. The life cycle of each species of rice cyst nematode is completed in 24–30 days and there are several generations during the host-growing season.

Damage symptoms are similar for most root-parasitic nematodes of rice. Field symptoms of *H. oryzicola* damage on rice include poor and patchy growth with occasional death of seedlings. Symptoms are similar to those of nutrient deficiency, including reduced tillering, stunting and leaf chlorosis (yellowing) [79].

Yield losses due to *H. oryzicola* are not well documented as the nematode generally occurs in association with other species. The nematode caused up to 56% reduction in the growth of rice plants grown in pots [80].

Rats

Among the vertebrate pests of rice rats are the most important. Since 2007, a spate of rodent outbreaks has led to severe food shortages in Asia, affecting highly vulnerable and food-insecure families [81]. Rodent-population outbreaks that led to severe food shortages in Mizoram (India), Chin State (Myanmar), Chittagong Hill Tracts (Bangladesh) and upland provinces of Lao PDR. In Laos, emergency food assistance was required for 85 000 people. In 2009, high rodent losses also occurred in lowland irrigated rice-based systems in the Philippines, Myanmar and Indonesia

As indicated, rats occur in both rainfed upland and lowland rice crops. Both the wet and dry seasons are favorable for rat reproduction and crop damage. In rainfed rice crops, rodents have their greatest impact in the wet season. The availability of food, water and shelter are factors, which provide optimum breeding conditions. The presence of grassy weeds also triggers their development.

Rice field rats feed at night with high activity at dusk and dawn. In the daytime, they are found among vegetation, weeds, or maturing fields [46]. During the fallow period, they utilize major channels and village gardens as prime habitats. At tillering, 75% of time they are in burrows along the banks and after maximum tillering, 65% of the time they are in rice paddies.

Rats feed in the seedbed and in the field. Damage in the seedbed can be due to rats consuming seeds directly or pulling up germinating seeds later on. In recently transplanted fields rats cut or remove entire seedlings. The result is missing hills. Rat damaged tillers are cut near the base in a distinct 45 angle. At the booting stage of rice growth, rats cut or bend older tillers to reach the

Table 7 Pests of rice and their geographical distribution – rats

Rats	Asia	Africa	Europe	N. America	S. America	Australia
Smaller bandicoot *Bandicota bengalensis*	X					
Soft furred field rat *Millardia meltada*	X					
Indian gerbil *Tatera indica*	X					
Rice rat *Oryzomys palustris*				X		
Ricefield rat *Rattus argentiventer*	X					
Pacific rat R. *exulans*	X					
Black rat R. *rattus*	X	X	X	X	X	X
Philippine ricefield rat R. *tanezumi*	X					
West African shaggy rat *Dasymys rufulus*		X				
African grass rat ('Agouti') *Arvicanthis niloticus*		X				

developing panicles. As the crop matures, rats cut or bend tillers to eat the ripening grain. At the grain ripening stage, rat damage on the grains is similar to bird damage. Damage is usually low during the vegetative stage, increasing rapidly after the flowering stage. The increased damage results from the greater number of rats due to increased cover and food. Rat damage delays grain maturity and can cause severe yield loss. http://www.knowledgebank.irri.org/index.php?option=com_zoo&task=item&item_id=958&Itemid=737.

Rats are one of the important biotic constraints to rice production in the Asia-Pacific region where they commonly cause annual pre-harvest losses between 5 and 10% [46]. According to Khan [82], losses of 5% of rice production to rats, in 11 Southeast Asian countries, amounts to approximately 30 m *t*-enough rice to feed 180 m people for 12 months.

The major rats in global rice production are listed in Table 7. Of these, the ricefield rat, *Rattus argentiventer* is the major agricultural rodent pest across much of island and mainland Southeast Asia.

The black rat, *Rattus rattus*, of the house rat complex, probably originating in Southeast Asia, now occurs in all rice growing regions of the world. The African grass rat, *Arvicanthis niloticus*, is primarily restricted to the African Sahel where it is a pest of upland and lowland rice. It also serves as a culinary delicacy in African diets in the form of 'agouti'.

Ricefield rat

The rice field rat, *Rattus argentiventer* is one of the more aggressive species of rats and is more common in open situations such as rice fields <http://www.cabi.org/isc/datasheet/46833>. *Rattus argentiventer* can be found throughout Southeast Asia as a major rodent pest in rice fields <https://en.wikipedia.org/wiki/Ricefield_rat>.

Rattus argentiventer is the major agricultural rodent pest across much of island and mainland Southeast Asia. Crop losses in rice-growing areas due to this species are typically in the order of 10–20%. Losses are generally higher in the second crop in areas where double and triple cropping are practiced and rat densities are especially high. For fields positioned close to refuge habitats such as canals or extensive upland areas, chronic losses of 30–50% are reported http://www.knowledgebank.irri.org/index.php?option=com_zoo&task=item&item_id=958&Itemid=737.

Black rat

The black rat, *Rattus rattus*, is part of the house rat complex. Other common names are house rat, roof rat and ship rat [46, 83]. The black rat occurs in all regions (Table 7). The global population of *R. rattus* represents a complex of five genetically distinct taxonomic groups [84]. This rat complex, probably originating in Southeast Asia, is made up of a number of closely related species that interbreed across part of their ranges [46]. The black rat is among the world's worst invasive species, having spread from Europe across the globe in close association with the spread of human settlement.

The nest is usually made of leaves or some other dry, soft material drawn together into a bundle and placed in any convenient confined place: a burrow or among rocks; in tree hollows and fallen logs; in tall grass or dense shrubs; in roof thatch or wall cavities; in piles of straw [83]; in harvested fields; and among stored sacks of grain [46].

Weeds

Classification of weeds

There are numerous weed species in rice (Table 8) and they are important biotic constraints. They can severely affect

Table 8 Rice pests and their geographical distribution – weeds

Weeds	Asia	Africa	Europe	N. America	S. America	Australia
Ageratum conyzoides (Asteraceae)		X				
Alisma plantago-aquatica (Alismataceae)			X			
Alisma triviale (Alismataceae)				X		
Alternanthera philoxeroides (Amaranthaceae)	X	X	X	X	X	X
Amaranthus spinosus (Amaranthaceae)	X	X	X	X	X	X
Ammania auriculata (Lythraceae)		X		X		
Ammania prieureana (Lythraceae)		X				
Bacopa repens (Plantaginaceae)				X	X	
Bolboschoenus maritimus (Cyperaceae)		X	X			
Brachiaria lata (Poaceae)		X				
Ceratophylletum demersi (Ceratophyllaceae)			X			
Chromolaena odorata (Asteraceae)		X				
Cleome viscosa (Cleomaceae)	X	X		X	X	X
Commelina benghalensis (Commelinaceae)	X	X				
Cynodon dactylon (Poaceae)		X				
Cyperus difformis (Cyperaceae)	X	X		X		
Cyperus esculentus (Cyperaceae)		X				
Cyperus halpan (Cyperaceae)		X				
Cyperus iria (Cyperaceae)	X	X				
Cyperus rotundus (Cyperaceae)	X	X				
Dactyloctenium aegyptium (Poaceae)	X					
Digitaria ciliaris (Poaceae)	X					
Digitaria horizontalis (Poaceae)		X				
Echinochloa colonum (Poaceae)	X	X		X		
Echinochloa crus-galli (Poaceae)	X		X	X		X
Echinochloa crus-pavonis (Poaceae)		X				
Echinochloa oryzoides (Poaceae)				X		
Echinochloa phyllopogon (Poaceae)				X		
Echinodorus cordifolius (Poaceae)				X		
Eclipta alba (Asteraceae)	X			X	X	
Eclipta prostrata (Asteraceae)	X	X				
Eichornia crassipes (Pontederiaceae)	X	X	X	X	X	X
Eleusine indica (Poaceae)	X					
Euphorbia heterophylla (Euphorbiaceae)		X				
Fimbristylis littoralis (Cyperaceae)		X				
Fimbristylis miliacea (Cyperaceae)	X					
Glyceria declinata (Poaceae)			X	X		X
Heteranthera limosa (Pontederiaceae)				X	X	
Imperata cylindrical (Poaceae)		X				
Ischaemum rugosum (Poaceae)		X				
Leersia hexandra (Poaceae)		X				
Leptochloa fascicularis (Poaceae)				X		
Leptochloa panicoides (Poaceae)				X	X	
Ludwigia abyssinica (Onagraceae)		X				
Ludwigia octovalvis (Onagraceae)	X	X			X	X
Mariscus cylindristachyus (Cyperaceae)		X				
Monochoria vaginalis (Pontederiaceae)	X					
Najadetum minoris (Hydrocharitaceae)			X			
Najadetum marinae (Hydrocharitaceae)			X			
Najas graminea (Hydrocharitaceae)	X		X	X		
Najas guadalupensis (Hydrocharitaceae)				X		
Oryza barthii (Poaceae)		X				
Oryza longistaminata (Poaceae)		X				
Oryza rufipogon (Poaceae)	X			X		
Panicum laxum (Poaceae)		X				
Paspalum distichum (Poaceae)	X					
Paspalum scrobiculatum (Poaceae)		X				
Portulaca oleracea (Portulacaceae)	X					
Potamogeton nodosus (Potamogetonaceae)			X	X		
Red rice (*Oryza sativa*) (Poaceae)		X	X	X	X	
Rhamphicarpa fistulosa (Orobanchaceae)		X				X
Rhynchospora corymbosa (Cyperaceae)		X				
Rottboellia cochinchinensis (Poaceae)		X				

Table 8 (Continued)

Weeds	Asia	Africa	Europe	N. America	S. America	Australia
Sagittaria longiloba (Alismataceae)				X		
Sagittaria montevidensis (Alismataceae)				X		
Scirpus fluviatilis (Cyperaceae)				X		X
Schoenoplectus mucronatus (Cyperaceae)			X			
Scirpus maritimus (Cyperaceae)	X					
Scirpus mucronatus (Cyperaceae)	X		X	X		
Sphenoclea zeylanica (Sphenocleaceae)	X	X				
Striga asiatica (Orobanchaceae)		X				
Striga aspera (Orobanchaceae)		X				
Striga hermonthica (Orobanchaceae)		X				
Trianthema portulacastrum (Aizoaceae)		X				
Typha spp.(Typhaceae)	X		X	X		

rice production if not properly managed. Weed species are classified according to (1) the structure of the leaves and stem, or morphology, (2) life cycle and (3) habitat [5, 9, 85, 86]. These classification schemes often reflect important biological and /or ecological features that are important in weed management.

1. Morphologically weeds are classified as: *Monocotyledons* (grasses and sedges) and *Dicotyledons* (broadleaved).
2. Weeds are divided into two classes according to the length of their life cycle: *Annuals* and *Perennials.*
3. Weeds are grouped on the basis of their adaptation to habitat: *Terrestrial, Emergents* (establish themselves before flooding but are adapted to rising water and prolonged flooding, and thus continue to compete with rice), and *Aquatic.*

Weeds as alternate hosts for insect pests and diseases

According to Islam and Catling [46] at least 155 weed species serve as alternate hosts to the major rice insect pest species while the major rice diseases have more than 80 weed species that serve as alternate host plants to cultivated rice, *Oryza sativa.* For insects, grasses comprise 63% of these, sedges 10%, broadleaved plants 6% and other field crops 21%. The proportion for diseases is similarly divided among these four host plant types. The major grass serving as an alternate host for rice insects is *Echinochloa* spp., followed by *Eleusine indica*, *Leersia hexandra* and seven species of *Oryza* wild rices, six species of *Panicum* and five species of *Paspalum*. The same four leading species of grasses and eight *Oryza* rices are also the dominant grasses harboring rice diseases. The most important sedges for insects and diseases are overwhelmingly several *Cyperus* species and of the other crops associated with rice the gramineous maize, wheat, sugarcane and millet are dominant.

Rice-weed competition

Weeds, through competition with rice, are important biotic constraints. Rice and weeds are closely related, have similar requirements for growth and development, and thus compete fiercely with each other. The degree of competition depends on rainfall, edaphic (soil) factors including nutrients, weed density, rice variety, duration of rice and weed growth, and crop age when competition starts [46]. In theory, the amount of light, water and nutrients in a given rice environment is fixed and whatever is used by one plant species is not available for any other.

Competition for light occurs throughout the growth of the plant, and the light requirement varies with crop growth stage [87]. Weeds compete with rice by growing faster and shading rice leaves with their large, horizontal leaves. The shading effect is most severe during the seedling stage. The period 30–45 days after planting is also critical for serious weed competition; from 45 to 60 days rice plants are able to suppress later germinating weeds. Low light intensity after flowering decreases rice dry matter.

Water shortage at any crop growth stage reduces yield, but more so if the stress occurs during the reproductive stage. Rice is a C_3 plant. Many vigorous dry land weeds, however are, C_4 plants having a higher photosynthetic capacity and lower water requirements and are thus better competitors than rice under dryland conditions. With flooding, C_4 plants are mainly replaced by C_3 plants, which offer less competition to rice. Rice and weeds also differ in their tolerance to drought because of differences in root distribution and elongation rate, genetic tolerance for low water availability in plant tissue and control of water loss through transpiration [88].

Nitrogen, phosphorus and potassium are the three major plant elements that determine growth and yield [87]. Many weed species have a nutrient uptake similar to rice but have a higher use efficiency. In general, plants with an efficient water uptake also have an efficient nutrient uptake.

Characteristics of successful weeds

Weed competitiveness and growth. Weeds have developed diverse strategies for growth and completion. Some weeds produce large seeds (enabling rapid seedling growth); some are climbers, taller, higher rates of photosynthesis, faster growth, larger leaves and deeper root systems than rice (enabling the exploitation of nutrients). Weeds are also highly adaptable to a changing environment (climate change and global warming) [89] where under favorable conditions they grow larger and produce many seeds.

Reproduction and dispersal. Seeds of many weeds (e.g. red rice) ripen non-synchronously and shatter before the rice crop matures [90]. Some annual weeds have short life cycles and produce several generations per year. Perennial weeds reproduce both sexually and vegetatively by means of underground reproductive organs. Many viable weed seeds remain dormant even under favorable conditions. This abundant seed production and long dormancy period results in buildups of large seed reservoirs in the soil and many seeds surviving there for several years. Wind, water and animals including humans [91] disperse mature weed seed and fruits. Flowing water is an important medium for the spread of weed seeds in rice fields.

Weed severity and losses

Weeds are incredibly opportunistic and will occupy any crop space suitable for plant growth. They are always a threat to the rice crop and may cause total crop failure. Weeds affect rice production in several ways [46]:

- They reduce the yield through competition for nutrients, soil moisture and sunlight.
- Raise production and processing expenditures by increasing the cost of control, replacing nutrients and water loss.
- Lower rice grain quality by causing admixtures of wild rice and other weed seeds that reduce the market value of rice.
- Reduce flow of water in irrigation and drainage channels resulting in seepage, flooding and breaks in canal banks.

Weeds are the cause of serious yield reduction problems in rice production worldwide. Losses caused by weeds vary from one country to another, depending on the predominant weed flora and on the control methods practised by farmers [92]. Two examples give an idea of the dimensions of the problem. In China, 10 MT of rice are lost annually due to weed competition [93]; such a quantity of rice is sufficient to feed at least 56 million people for 1 year. In Sri Lanka, a country considered self-sufficient in rice, weeds are the major biotic stress in rice production and account for 30–40% of yield losses [94].

In West Africa, parasitic weeds are among the most destructive and problematic weeds to control [95]. The most important parasitic weed species in rice are *Striga asiatica*, *Striga aspera*, *Striga hermonthica* and *Rhamphicarpa fistulosa*. These parasitic weeds, which survive by siphoning off water and nutrients from host crops, have invaded 1.34 million hectares of rainfed rice in Africa, affecting an estimated 950 000 rural households.They are becoming more severe due to an intensification of agricultural production and climate changes.

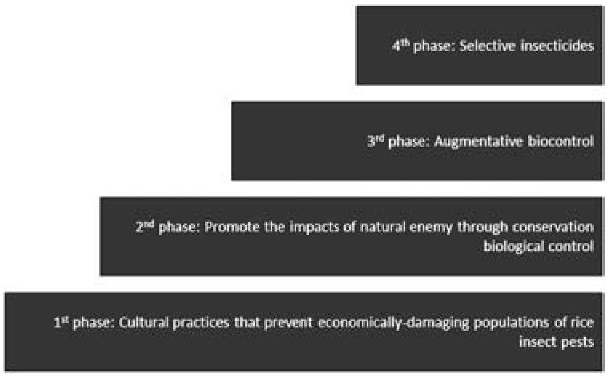

Figure 1 Conceptual framework for rice IPM (adapted from Zehnder *et al.* [102])

The areas affected by parasitic weeds are home to some of the world's poorest farmers. Studies by AfricaRice and partners have shown that parasitic weeds seem to predominantly affect women farmers in Africa as they are often forced to grow rice on the most marginal and parasitic weed-infested plots (http://africarice.blogspot.com/2017/01/africas-rice-farmers-lose-200-million.html).

Parasitic weeds threaten rice production in at least 28 countries in Africa that have rainfed rice systems. The most affected countries are Burkina Faso, Cameroon, Côte d'Ivoire, Guinea, Madagascar, Mali, Nigeria, Sierra Leone Tanzania and Uganda. AfricaRice researchers warn that these parasitic weeds are spreading fast in the rainfed rice area and if nothing is done to control them, the damage will increase by about US $30 million a year (http://www.sciencedirect.com/science/article/pii/S016788091630528X).

Management of Rice Pests

Concepts and options for rice IPM

Pre-harvest yield losses due to rice pests can be significant. This is especially so under pest outbreak scenarios. Irrigated rice has been shown to be an agroecosystem with rich biodiversity and a redundant food chain [96, 97]. Pesticide abuse negatively affects the natural enemy communities, shortens the food chain length and increases the propensity for pest outbreaks in irrigated rice ecosystems [98–100]. An alternative framework for insect pest management is needed to address the pest vulnerability of rice production without introducing a higher risk of pest outbreaks [12].

Wyss *et al.* [101] and Zehnder *et al.* [102] proposed a conceptual framework for arthropod pest management in organic crop production (Figure 1). In this framework, arthropod pest management strategies are classified into four 'phases'. The framework prioritizes pest management options that will prevent damaging levels of pests (phase 1 and 2) and minimize the need for curative actions (phase 3

Table 9 Cultural practices that prevent the development of economically-damaging populations of rice pests. Modified from [103] and [46].

	Single field scale	Community scale
Primary practices	• Deployment of resistant rice varieties against stem borer and brown planthopper in Asia and rice water weevil in North America	• Insect light traps using blue light were used to control stemborer moths, *Chilo suppresalis*, in paddy fields across Japan during WW II and the post-war years
Secondary practices	• Fertilizer management affects hopper and stem borer populations in Asia • Delayed planting date to avoid population peak of small rice stink bug in South America • Water and planting date management affects rice water weevil population in North America • Transplanting older seedlings reduces exposure to vegetative stage pests (caseworm and whorl maggot) in Asia • Removing weeds from rice fields and surrounding paddies destroys alternate host plants of insects and diseases and reduces shelter for rats • Roguing of diseased plants in the nursery prevents spread of some diseases in the field	• Synchronous planting affects the incidence of tungro, a viral disease vectored by the green leafhopper in Asia • Crop rotation breaks the life cycle of the gall midge • Rice cropping frequency – A dry season fallow period limits the abundance of whorl maggot, leaf- and planthoppers in Asia • Planting time – Early planting limits populations of the gall midge and late planting lowers the incidence of leaffolders in Asia • Planting early maturing varieties after a rice-free period effects stem borer and gall midge populations in Asia • Harvesting method – Cutting height influences survival rate of stem borers • Flooding rice stubble after harvests drowns armyworms and stem borers • Tilling soil directly after harvest kills stem borer larvae, armyworm pupae and grasshopper eggs and prevents unwanted ratooning. Ratoon crops serve as hosts of insect-vectored virus diseases

and 4). We will adopt and modify this conceptual framework to structure the discussion on various rice pest management options in rice ecosystems.

Cultural practices

Generally, two types of practices are found under this phase: (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 probably form the earliest methods of pest management in rice and include mechanical and physical removal of insect and rodent pest populations. These practices are typically labor intensive in nature. In terms of the optimum spatial scale, these cultural practices can be further classified into two: (1) those that operate in single-field scale and (2) those that operate in community scale (i.e. covers multiple fields within a locale). Litsinger [103] catalogued a number of cultural practices that prevent the development of economically damaging populations of rice pests and we classify these practices according to their principal intent (e.g. primary and secondary practices) and optimum spatial scale in Table 9.

Of the cultural practices listed above, deployment of host plant resistance (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.

Host plant resistance: insect and disease adaptation and deployment strategies. Much work has been done to identify resistance genes, and breed them into elite varieties [104, 105]. Sources of resistance have been identified for many of the rice insect pests [106] and diseases [107], especially in Asia.

Resistance durability is the primary challenge in host plant resistance utilization against rice insect pests. Rice pest populations showed rapid adaptation against the deployed resistant varieties. This is especially well documented in rice-brown planthopper systems [108].

Mundt [109] listed 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. Gene rotation involves a regional deployment of a resistance gene, monitoring of pest virulence/adaptation to the deployed gene within the region and rotation to another resistance gene upon detection of pest adaptation. There is evidence that this deployment scheme is feasible in prolonging durability against rice blast disease [110]. The challenge lies in the implementation of regional monitoring schemes to detect the target pest's adaptation to the deployed gene.

While gene rotation subjects the same cropping space to two or more resistance genes over time, field deployment of a mixture of varieties essentially subjects various parts of the cropping space to two or more varieties with different levels of resistance in a given period. Large-scale trials in China showed that a mixture of resistant and susceptible varieties suppressed rice blast severity and reduced the need for fungicide application [111]. However, the report did not monitor the effect of the strategy in prolonging the durability of resistance against rice blast.

A number of studies reported that pyramiding two or more resistance loci resulted in higher resistance compared with monogenic lines, as measured by the target pest's feeding, settling, survivorship, population growth and damage on host plants [112–114]. However, Sharma *et al.* [115] showed that a pyramided line (incorporating Bph1 and bph2 genes for brown planthopper resistance) had the same resistance level as introgression lines carrying Bph1 alone. None of these studies measured the effects of pyramiding resistance genes to the durability of the resistance.

Gene function and resistance mechanisms associated with identified resistance genes against rice pests are not fully understood [104]. Moreover, the mechanisms and genetic/physiological basis for pest adaptation to resistant rice varieties are not always clear. Without this information, it is difficult to predict how the different deployment strategies will delay pest adaptation toward resistant rice varieties.

Fertilizer management. In general, fertilizer management affects rice insect pest populations by modifying rice plants' suitability for and attractiveness toward herbivorous insects [116–125]. Increased nitrogen fertilizer rate was associated with a longer larval development duration and higher oviposition rate of the leaffolder (*C. medinalis*) [116]. Leaffolder female moths preferred rice plants with higher fertilizer rates to lay their eggs compared with plants with lower fertilizer rates [117]. A small-scale field experiment confirmed that the number of leaffolder eggs found on plots with high fertilizer rate (~150 kg/Ha) was higher than those found on plots with lower fertilizer rates (~0 and 75 kg/Ha). Furthermore, the ratio between natural enemy and leaffolder larval abundance was correlated negatively with nitrogen fertilizer rate and, consequently, the survivorship of leaffolder larvae was the highest in plots receiving high amounts of nitrogen fertilizer [117].

Lu *et al.* [120] (2004) reported a positive correlation between rice leaf nitrogen content and brown planthopper nymphal survivorship, longevity of adult females, female fecundity and egg hatching rate. Additionally, higher leaf nitrogen content was associated with faster nymphal development of brown planthopper. Taken together, these findings indicate that excessive nitrogen fertilization rate may lead to faster population development and higher maximum population levels of brown planthopper. Nitrogen fertilizer regimes may affect brown planthopper population's ability to grow on resistant or tolerant varieties. Heinrichs and Medrano [126] recorded a positive correlation between nitrogen fertilizer rate and the number of brown planthopper populations developing on Triveni, a tolerant rice variety with some antibiosis activity, and IR60, a resistant variety with high antibiosis.

Nitrogen fertilizer regime affected rice plant's host suitability for stem borer and the plant's ability to compensate for tiller loss. Jiang and Cheng [121] reported that striped stem borer's larval weight gain and development were positively correlated with nitrogen fertilizer rates. Moreover, nitrogen, as a plant nutritional factor, contributes to the ability of rice to produce new tillers. Therefore, the plants compensated for striped stem borer injury between the low and medium range of nitrogen fertilizer rate but not under high or excessive range of nitrogen [121].

The form of fertilizer may have an impact on rice herbivorous insects. White-backed planthoppers feeding on rice with poultry-manure fertilizer had lower nymphal survivorship, reproductive rate and egg hatching rate compared with those feeding on plants with inorganic fertilizer [127, 128]. The same effect of lower nymphal survivorship on organically fertilized rice plants was observed with brown planthopper [127]. Specifically, the leaves of organically fertilized plants contained significantly lower amount of asparagine, an amino acid, compared with those with inorganic fertilizer. Asparagine acts as a feeding stimulant for brown planthoppers [129] and its absence, or low titer, has been associated with planthopper resistance in various indica and japonica rice varieties [130, 131].

Conservation biological control

Natural pest regulation in irrigated rice ecosystems. Among cultivated plants, irrigated rice constitutes a complex ecosystem with a relatively high species diversity and redundant food web [96, 97]. Various life stages of herbivorous insects in rice ecosystems are preyed upon and parasitized by predators and parasitoids from a number of classes and orders, including araneae [132, 133], orthopterans [117]), coleopterans [134], aquatic and terrestrial heteropterans [135, 136], hymenopterans, strepsipterans and dipterans [137].

Settle *et al.* [99] showed that across irrigated rice production fields in Java, generalist predators (e.g. spiders, mirid bug) were always abundant early in the cropping season. An increase in the organic matter before the beginning of the season resulted in the increased decomposer abundance and led to even higher levels of predator populations. These correlations indicated that predators in rice ecosystems utilize decomposer communities as alternative prey before the arrival of phytophagous insects [99]. The widely practiced staggered planting in intensive rice production areas may further ensure the continuous availability of prey and hosts in rice fields and contribute to the abundance of natural enemy populations in this ecosystem [100].

Conservation biological control in rice ecosystems capitalizes on and enhances the natural pest regulation provided by these prevalent natural enemy communities in rice fields. Annual monoculture cropping systems are often associated with high disturbance regimes on the natural habitat for natural enemies. High usage of pesticides and potential lack of adult food source and shelter are among the disturbances affecting the natural enemy populations in these cropping systems [138]. 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.

The effects of insecticide application on natural enemy and pest populations. In a descriptive work on insect population dynamics as affected by early insecticide application (20–50 days after transplanting), Schoenly *et al.* [96] found a stark difference in pest and natural enemy populations between sprayed and unsprayed fields. By mid-season, natural enemy abundance was higher in the unsprayed field compared with that in the sprayed field. On the other hand, herbivorous insect populations were higher by mid-season on the field receiving three early insecticide applications. Indeed when food webs were constructed for the two field types, the authors found that the mean length of the food chain was shorter in fields receiving early insecticide application. This food chain shortening continued for about 40 days after the first spray. The natural enemy population eventually rose in the field receiving early insecticide application, yet the damage due to increased herbivore abundance during the mid-season might have already been done.

At least two mechanisms contribute to this dramatic increase in pest population due to early insecticide applications. First, Schoenly *et al.* [96] linked a reduction in natural enemy population immediately after insecticide application to a rapid increase in herbivore abundance. The increase in the herbivore population has indeed been attributed to the temporal release of herbivores from natural enemies following early insecticide applications [29, 139, 140].

The second mechanism involves ecological fitness. Chelliah *et al.* [141] and Chelliah and Heinrichs [142] reported an increase in the reproductive rate of brown planthopper in response to a sub-lethal dose of insecticide. This phenomenon, in which a sub-lethal dose of a select insecticide increases ecological fitness parameters of certain insects, is termed ‘hormesis.’ Hormesis has recently received further attention and studies on different rice pest species, using various active ingredients, have been published [143–148]. Stimulation of ecological fitness parameters by a sub-lethal dose of insecticide forms the second mechanism explaining the rise in pest population as affected by insecticide application [149].

What factors drive the practice of early insecticide application? Heong *et al.* [150] reported that early insecticide application is often driven by farmers’ perception of defoliators’ ability to affect yield. Indeed, defoliator pests that produce conspicuous injuries, such as the leaffolder, often infest rice fields early in the season. Yet, empirical and simulation studies show that early stage defoliation by leaf folder only resulted in a rare occurrence of minor yield loss [150, 151]. Consequently, much of the early season application of insecticides was based on exaggerated estimation of plant damage due to leaffolder and likely to be uneconomical [150]. These observations led to the formulation of a simple rule of thumb: ‘insecticide spraying for leaf folder control in the first 40 days after sowing or transplanting in the field is not needed’ [152]. This simple message, supported by public media and an entertainment education campaign, has been shown to successfully change farmers’ practice in the Mekong Delta, Vietnam [153, 154].

A number of caveats need to be taken to complement this simple message. While irrigated rice may be an inherently resilient ecosystem against pests, it is possible that insect pest populations occasionally reach damaging levels early in the season, perhaps due to a particularly high immigration rate or high degree of planting asynchrony. Unfortunately, economic injury levels for early rice stages that take into account natural enemies’ capacity to provide biological control are not available and this lack of knowledge hampers our ability to make judicious pest management decisions.

The effects of different active ingredients on rice natural enemies vary widely [155–160]. ‘Reduced risk’ insecticides, due to their selectivity against natural enemies and other non-target organisms, have recently been developed. These newer insecticides are not commonly used in rice production, partly due to their relatively expensive costs [161]. To test the effects of these reduced risk insecticides on field populations of natural enemies, when applied early in the season, well designed research needs to be conducted. Information from these studies should then be used to evaluate whether these ‘reduced risk’ insecticides may become options for rare occasions of early insecticide application as dictated by pest population levels.

Habitat management for natural enemy conservation. Various habitat management schemes within agricultural fields, for example by intercropping and introduction of wildflower strips or plants repellent to herbivores, were shown to significantly suppress herbivore populations, enhance natural enemies and reduce crop damage [162]. While the limitation on early insecticide application enhances rice natural enemies by reducing the known effect of a disturbance regime (insecticide), habitat management schemes typically provide resources (e.g. alternative or complementary food sources, shelter) to the natural enemy species.

In the Asian rice ecosystem, much effort has been invested in designing a habitat management scheme in which flowering plants are introduced on rice bunds to conserve natural enemies [137, 163–166]. Introduction of flowering plants seemed to have a primary benefit of food provisioning (e.g. pollen, floral and extrafloral nectar) to members of the natural enemy community [167]. Indeed many predators and parasitoids are known to utilize non-prey food sources, usually to satisfy their need for metabolic energy [168]. Laboratory studies showed that, compared to a water control, the presence of sesame flower (*Sesamum indicum*) as a food source increased the adult longevity of planthopper parasitoids (*Anagrus optabilis* and *Anagrus nilaparvatae*) [166] and stem borer parasitoids (e.g. *Apanteles ruficrus*, *Cotesia chilonis* and *Trichogramma chilonis*) [166]. A similar laboratory study showed that the adult longevity of a predatory mirid bug, *Cyrtorhinus lividipennis*, was significantly increased in the presence of sesame as well as other flowers (e.g. *Tagetes erecta*, *Trida procumbens*, and *Emilia sonchifolia*) compared with water or nil controls [169]. Furthermore, these controlled experiments showed that the presence of sesame flowers increased the parasitism and predation rates of the natural enemies compared with water or nil controls [169].

These benefits, observed in controlled experiments, might not all translate to enhancement of natural enemies at the field level. Yet, in the case of sesame flowers, the natural enemy benefits reported in laboratory studies were reproduced at the field scale. In a factorial study with combinations of sesame borders and pesticide applications, fields with sesame borders and no pesticide applications had the highest predator and parasitoid abundances compared to all other combinations (e.g. no sesame border and no pesticide application, no sesame border with pesticide application, with sesame border with pesticide application) [164]. Indeed, the same report contains a multi-country comparison where rice fields with nectar-bearing flowers on their borders had significantly lower pest populations, received less insecticide applications (as guided by farmers' decision), and produced higher yields compared with control fields [164].

Augmentative biological control

While the irrigated rice ecosystem constitutes a redundant food web it is plausible for the insect pest populations to occasionally reach economically damaging levels. Then, curative actions are needed and, whenever available, augmentative biological control should form the first curative option. In contrast to conservation biological control, the aim of which is to improve the impact of the 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 activities 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 with the expectation that the small number of released natural enemies will multiply rapidly) or within a short period of time in season (*innundative* biological control [*mass releases*] where the natural enemy is not likely to reproduce fast enough).

Rombach *et al*. [170] provided a bibliography on pathogens of rice insect pests from 1960 to 1985 and listed members of all fungal major groups, bacteria, viruses and nematodes as potential biological control agents of rice insect pests. Since then, a number of studies have continued to show the efficacy of primarily two entomopathogenic fungal genera, *Metarhizium* and *Beauveria*, on rice pests [170–175]. Additionally, in a laboratory experiment using an artificial diet, toxins produced by *Bacillus thuringiensis* (Bt) have been shown to inhibit feeding by larvae of the rice striped borer, *Chilo suppressalis* (Walker) [176].

One of the criticisms against the use of invertebrate pathogens as augmentative biocontrol agents in rice production is the relatively long period it takes for control and the limited efficacy at field scale [177]. Rombach *et al.* [178], for example, recorded very low level of mortality after field application of five entomopathogenic species (including *Beauveria bassiana* and *Metarhizium anisopliae*) 7 days after treatment (0–4% mortality rate). Yet the mortality rate reached 70–100% at 21 days after treatment. Further development of biological control agents will have to address these criticisms by identifying highly virulent fungal strains, optimizing formulation and, perhaps, considering a mixture of augmentative biocontrol with other control options.

Insecticides

Chemical insecticides should only be used, as a last resort, when all other tactics in the arsenal of IPM options, including biopesticides, are not effective in managing pest populations. If insecticide applications are necessary, those showing a greater selective toxicity to the pest than to the natural enemies, should be employed. There are a number of considerations to guide insecticide application in rice ecosystems: application timing, selectivity of active ingredients and resistance among pest populations associated with insecticide overuse. For the insecticide application to be profitable, application decision must be guided by an estimate of economic loss that may be incurred if no curative action is taken. This is usually done by introducing an economic threshold value (ETL) for pest populations to guide decisions. Furthermore, improper selection of the insecticide and timing of insecticide application may prove harmful to the indigenous natural enemy community and its attendant pest regulation function [96]. It should be noted that some active ingredients were shown to be more toxic to the natural enemy than the pest species [155]. Finally, overuse of insecticides may lead to the development of insecticide resistance among insect pest populations [179, 180].

Economic action thresholds. Economic injury level, defined as 'the lowest population density that will cause economic damage', is a keystone of IPM theory [181]. A number of economic injury levels and economic action thresholds against individual rice pests have been developed and tested in Asia [182–186] and North America [187]. In large scale testing against rice bug and plant- and leafhoppers in the Philippines, Litsinger *et al.* [183] reported that while implementation of action thresholds typically resulted in significantly higher rice yield compared with untreated controls (by about 0.3–0.5 ton/ha), they are not always profitable to farmers.

A number of factors may contribute to this result: (1) While the development of an economic injury level typically takes into account the commodity market value and the cost of management action, in practice the economic injury level is not adjusted to account for temporal fluctuation and spatial variation in rice price, (2) Most of the economic injury levels on rice pests do not take into natural pest regulation potential of indigenous natural enemies, and (3) Most of the economic injury levels on rice were developed on a limited number of susceptible rice varieties [182].

Due to the limitations above, the practicality of using action thresholds in rice ecosystems, especially among smallholder farmers, has been questioned [188]. Since the available economic threshold values do not typically take into account the local and temporal specifics (in terms of price variability, natural enemy populations and varieties planted, for example), efforts to use economic thresholds may backfire and trigger unnecessary application of insecticides.

Selectivity against natural enemies. Studies have shown that insecticidal active ingredients vary in their selectivity against natural enemies in different Asian countries. In the Philippines, Fabellar and Heinrichs [155] showed that deltamethrin, chlorpyrifos and endosulfan are more toxic to *Pardosa pseudoannulata*, a common predatory spider, compared with the brown planthopper. Indeed, a number of reports stated that while deltamethrin was associated with brown planthopper resurgence [149, 189, 190], no such resurgence was observed for the green leafhopper [155, 191]. In Japan, deltamethrin was found to be more toxic to a number of predatory spiders, mirid bugs and *Haplogonatopus apicalis*, a drynid wasp, compared with the brown planthopper [159]. Using a risk quotient approach (calculated as the ratio between recommended field dose of a given active ingredient and the LC_{50} of the same active ingredient to a given natural enemy), Zhao *et al.* [192] reported that all tested organosphosphates and carbamates posed high risks against *Trichogramma japonicum*, a parasitoid of rice lepidopteran pests, present in China. This means that the recommended field rates of these active ingredients are much higher than their comparative $LC5_{0s}$ against *T. japonicum*, in some cases more than 1000 times higher.

Insecticides may also affect the biological control function of natural enemies. In a cage study, Fabellar and Heinrichs [155] reported a significantly lower predation rate of *L. pseudonannulata* on plants treated with azinphos ethyl, an organophosphate insecticide, compared with spider on untreated plants.

In summary, active ingredients of different members of the organophosphates, pyrethroids, organochlorines and carbamates seemed to pose a high risk against various members of natural enemy communities in the rice ecosystem.

Insect resistance to insecticide. Insect resistance to various active ingredients has been reported among different rice insect pest species across Asia. In 2006, resistance against imidacloprid was detected on brown planthopper populations collected in East Asia (Taiwan, China and Japan) and Vietnam but not on those collected in the Philippines. Additionally, resistance against fipronil was detected among whitebacked planthopper populations from East Asia, Vietnam and the Philippines [193].

Moderate resistance against buprofezin, an insect growth regulator, was widespread among white-backed planthopper populations collected in China in 2010–2011 [179]. An eleven-year survey showed a dramatic increase (up to 28 fold) in buprofezin resistance among Chinese brown planthopper populations between 1996 and 2006 [160].

Rice IPM Package of Practices

As previously discussed, the major practices for the management of rice pests, diseases and weeds are based on three major strategies: (1) cultural control, (2) host plant resistance, (3) biological control and (4) selective insecticides http://www.sciencedirect.com/science/article/pii/S167263081730001X Cultural control of rice pests refers to crop husbandry practices, used consciously or unconsciously by farmers that improve yield by reducing pest numbers. Host plant resistance refers to those heritable characteristics possessed by the plant which influence the ultimate degree of damage done by an insect or a disease. Biological control is defined as the action of predators, parasitoids, pathogens, antagonists or competitor populations to suppress a pest population, making it less abundant and damaging than it would otherwise be. Finally, selective insecticides are a type of pesticide that targets the pest and have a minimal impact on the natural enemy population.

Rice pest management packages are based on an integration of these control strategies. A rice pest management package of practices, for lowland irrigated rice, that integrates these three control strategies, developed in India by the Directorate of Plant Protection, Quararntine & Storage [194], and modified, is presented in Table 10 as an example.

Transfer of Rice IPM Technologies

Over the last two decades, two major dissemination mechanisms for rice IPM in Asia have taken shape: Farmer Field School (FFS) and Mass Media Campaign (MMC) [12]. FFS is a participatory training approach, involving both men and women farmers, that utilizes experiential and reflective learning principles. The approach improves farmers' capacities through a series of regular meetings with highly trained facilitators (typically extension workers or NGO staffers) in which the farmers conduct their own field experiments, learn to diagnose problems and formulate solutions [195]. The use of FFS as a means

Table 10 Rice pest management package (modfied from [194])

Crop stage	Management tactic	Purpose
Pre-planting		
Field preparation	Raise pre-crop of sesbania or sun hemp and incorporate 45 days old crop in soil during land preparation	Trap crop
	Tillage, removal of weeds and leveling to maintain an even level of water	Weed control: emerged weeds can be plowed under before planting rice
	Pre-sowing irrigation and tillage	Weed control: emerged weeds can be plowed under
	Cleaning of bunds (levees)	Removal of alternate hosts
	Sowing seeds of flowering plants, e.g. marigold, sesamum or flowering vegetables	Provide pollen for parasitoids and predators (Augmentative biocontrol)
	Set up plastic sheet barrier strips around the field	Rodent control
Seed selection	Select pure high-quality seeds free of disease, weed seeds and insect damage	Weed, nematode, disease control
	Select insect/disease resistant varieties	Genetic pest control
Nursery	Destruction of old nursery from previous crop	Weeds, insects and diseases
	Raising a healthy nursery	Tolerance to abiotic and biotic stresses
	Seed treatment with carbendazim 50% WP@ 2 g/kg seed or Trichoderma/Pseudomonas @ 5 g/kg of seed	Seed or soil-borne disesases
	Seed treatment with carbosulfan @ 2 g/kg seed	Root nematodes
	Seed treatment with imidacloprid 200 SL (20%) @ 0.25 l/ 100 kg rice seed with 10% solution of gum Arabica in 3.75 l of water just before sowing	Termites (in termite endemic areas)
Transplanting/ sowing	Timely sowing	Early planting may avoid leaffolder and virus damage
	Rice seedlngs should be free of weed seedlings at time of transplanting	Weed management
	Normal spacing of transplants plants with 30–36 hills/m^2 depending on duration of the variety	Provide sunlight for maximum growth and tolerance to pests
	In direct sown rice, crop should be sown in lines at recommended spacings	To facilitate inter-weeding operations
	Clipping of rice seedlings at time of transplanting	Minimize carryover of rice hispa, case worm and stemborer infestation from seed bed to transplanted fields
Vegetative growth to maturity	Mechanical weed control methods applied at 2–3 weeks after sowing and a second time at 4–6 weeks if necessary	Weed control
	No pesticide spray period for first 40 days after sowing or transplanting	Conserve beneficial arthropods
	Grow nectar plants on levees	Conservation of natural enemies
	If pesticide applications are necessary after 40 days apply biopesticides e.g. *Metarhizium*, *Beauveria bassiana*, *Bacilllus thuringiensis*, NPV or a botanical insecticide e.g. neem	Conserve beneficial arthropods
	Employment of soil health cards to provide information on soil management, use of balanced fertiliser and maintaining the productivity of farmland http://soilhealth.dac.gov.in/	Control of pest populations promoted by fertilizer
	Balanced use of fertilisers and micro-nutrients as per local recommendations	Reduce planthopper outrbreaks
	Splitting nitrogen applications	Control of planhoppers, bacterial blight and stem rot in endemic areas
	Maintain a thin layer of water on soil surface	Minimize weed growth
	Use of coir rope for dislodging insects from rice plants	Caseworm, cutworm, swarming caterpillar etc.
	Hand removal and destruction (burning) of disease and pest infected plant parts	Minimize diseases and pests in the field
	Set up yellow sticky traps	Minimize thrips and whiteflies
	Set up pheromone traps for stem borers	Monitor and to take up timely interventions
	Release of egg parasitoid *Trichogramma japonicum* and *T. chilonis* @100,000/ha on appearance of stemborer and leaffolder egg masses	Biocontrol (parasitization of pest egg masses)
Harvest		
	Harvest rice plants close to ground	Destroys insects in internodes/stubbles and exposes insects to birds
	After harvest flood fields thoroughly and plow with discs or rotators	Kills hibernating stemborer larvae

for rice IPM dissemination was first developed in the Philippines as a collaboration between International Rice Research Institute (IRRI) and the Philippines' Bureau of Plant Industry [196]. The FAO later launched a large-scale FFS campaign in Indonesia in the late 1980s. Participation in FFS on rice IPM has reduced insecticide use and increased yield over time [197]. FFS participants used much less pesticide and produced significantly more yield compared with control farmers [198]. Based on the success in Indonesia, FFS was adopted as a dissemination mechanism for IPM and other best agronomic practices across the globe [195].

However, the impact and cost effectiveness of FFS as a means for IPM dissemination has been contested. The major criticisms against FFS are its financial sustainability and effectiveness to spread information among non-participants. There are evidences that very limited, if any, diffusion of IPM knowledge and practices occurred between FFS alumnae and neighboring farmers [198, 199]. In light of the limited diffusion effects, out scaling of FFS to cover a significant farmer population may be crucial to achieve a large-scale impact of the IPM packages. However, Quizon *et al*. [200] observed high upfront and overhead costs of FFS upscaling to cover a meaningful farming population and concluded that FFS were financially unsustainable.

A FFS was launched in Vietnam in 1992, the project focused on farmers living around towns or main roads. Thus, there was a concern that the method may not reach farmers who live in areas outside town proper or with limited road access. A MMC was introduced in Vietnam specifically to reach these 'underserved' farmers [201]. There has been an evolution of the messages disseminated through MMC in Vietnam. A simple rule of thumb, 'insecticide spraying for leaf folder control in the first 40 days after sowing or transplanting in the field is not needed (No early spray – NES)', was formulated and the multimedia materials to communicate this message were designed through a participatory workshop that involved researchers, extension and agricultural communication specialists. The resulting MMC involved distribution of leaflets, posters, roadside billboards and radio dramas broadcast through local stations and played at coffee shops [152]. After 31 months of the MMC-NES in Long Anh province, Vietnam, the proportion of farmers who believed that early season spraying was required dropped from 77 to 23%. Reported spray frequency was also significantly reduced from 3.35 sprays per season to 1.56 sprays per season [152].

Between 1992 and 1997, both FFS and MMC-NES coincided in Vietnam providing an opportunity to compare the impacts of both interventions. In terms of reach, FFS trained 108 000 farmers in the study sites across Mekong Delta while MMC reached 2.3 million farmer households [153]. Both FFS and MMC-NES had effects on farmer beliefs. The percentage of farmers who believed that killing natural enemies can cause more pests are the highest among those exposed to both FFS and MMC-NES compared to those exposed to only MMC-NES. Furthermore, the percentage of farmers who believed that applying insecticides would increase yield is lower among those exposed to both interventions compared to those exposed to only MMC.

An evaluation study of both FFS and MMC-NES message was conducted in 2005 in three southern Vietnam provinces. The study showed that farmers exposed to either FFS and MMC-NES are more technically efficient in using pesticide compared with control farmers (i.e. those not exposed to either intervention). However, there is no statistical difference in the amount of insecticides used by farmers receiving MMC-NES compared with control farmers. This may mean that MMC-NES farmers were spraying the same amount of insecticides with better timing compared with control farmers, thus producing better technical efficiency. FFS farmers used statistically less insecticides compared with control farmers, however there was no difference in spray frequency between FFS and control farmers. This may mean that FFS farmers spray as frequently as control farmers with lower rates, perhaps as the results of following label dosage and better recognition of pest and beneficial insects [201]. The authors posit that the difference between their evaluation results of MMC-NES impact and previous studies [152, 202] may have stemmed from the chosen evaluation methodologies. Rejesus *et al*. [201] (2009) pointed out that previous evaluation studies for MMC impacts did not take into account the possible selection bias and endogeneity problem, which might affect the studies' inferences.

In 2002, a large-scale participatory experiment was conducted with 951 farmer collaborators in multiple Vietnamese provinces in the Mekong Delta to evaluate the effects of reducing pesticide, fertilizers and seed rates on rice farming productivity and profitability. This exercise showed that reducing input from the then current practice had no effect on productivity and improved profitability [202]. This large-scale participatory evaluation formed the basis for a message expansion disseminated through a MMC in Vietnam. The new campaign, locally termed 'Ba Giam Ba Tang' or 'Three reductions, Three Gains' promoted a reduction of pesticide, synthetic fertilizer and seed rates (i.e. three reductions) and promised savings in production costs, improved farmers' health and environmental quality (i.e. three gains). The campaign distributed leaflets and posters. Additionally, a radio drama and a 30-s TV commercial were broadcast over local radio and TV stations. An evaluation of this MMC was conducted in Can Tho and Tien Gang provinces. Two months after the launch of the campaign, 81 and 56% of surveyed farmers had heard of the campaign in Can Tho and Tien Gang, respectively [202]. The evaluation program monitored the changes in farmers' belief attitudes and input use (self-report) as affected by the campaign. Reductions of insecticide spray (∼13–33%), seed rate (∼10%) and nitrogen fertilizer rate (∼7%) were reported. Additionally, there was an overall change in belief attitudes favoring reduction of the targeted inputs [202]. Huelgas *et al.* [203] found an increase of US$92–118/ha in net income from An Giang province in Vietnam. However, economic assessment data from Can Tho province showed lower net income among 'Ba Giam Ba Tang' adopters compared with the non-adopters.

In conclusion, FFS is an effective educational tool to improve the farmers' capacity to manage their agroecosystem. This improvement translates to reduction in pesticide use and higher yield. However, the high cost and tendency for low diffusion effects to non-participants are the weaknesses of FFS. MMC is an effective method to communicate simple messages to a large farming audience. When designed correctly, the simple messages work to modify farmers' attitude and behavior. Both FFS and MMC increased the technical efficiency of pesticide use by farmers; however the household-level economic impact of MMC may vary with geographic location. FFS and MMC complement each other by creating a nucleus of farmers with in-depth understanding of agro-ecosystem management and ability to conduct their own field experiments while mass communicating simpler IPM messages toward a larger farming audience.

Acknowledgement

Preparation of this review was supported by the USAID Cooperative Agreement No. AID-OAA-L-15-00001 awarded to Virginia Tech.

References

1. Muthayya S, Sujimoto JD, Montgomery S, Maberly GF. An overview of global rice production, supply, trade, and consumption. Annals of the New York Academy of Sciences 2014;1324:7–14.
2. Food and Agriculture Organization of the United Nations. FAOSTAT. Available from: URL: http://www.fao.org/faostat/en/#data (accessed on 23 March 2017).
3. Seck PA, Diagne A, Mohanty S, Wopereis MCS. Crops that feed the world 7: rice. Food Security 2012;4:7–24.
4. Chang TT. Crop history and genetic conservation: rice – a case study. Iowa State Journal of Research, 1985;59:425–35.
5. De Datta SK. Principles and Practices of Rice Production. John Wiley & Sons, New York; 1981. 618 pp.
6. Phool CG, O'Toole JC. Upland Rice: A Global Perspective. International Rice Research Institute, Manila, Philippines; 1986.
7. Catling D. Rice in Deep Water. IRRI, Manila, Philippines; 1993. 559 pp.
8. Kende H, van der Knaap E, Cho H-T. Deepwater rice: a model plant to study stem elongation. Plant Physiology 1998;118 (4):1105–10.
9. Reissig WH, Heinrichs EA, Litsinger JA, Moody K, Fiedler L, Mew TW, *et al.* Illustrated Guide to Integrated Pest Managment of Rice in Tropical Asia. International Rice Research Institute, Los Baños, Laguna, Philippines; 1986. 411 pp.
10. Grist DH, Lever RJAW. Pests of Rice. Longmans, Green and Co. Ltd., London, UK; 1969.
11. Oteng JW, Sant'Anna R. Rice production in Africa: current situation and issues. International Rice Commission Newsletter; 1999. vol. 48.
12. Heinrichs EA, Nwilene FE, Stout MJ, Hadi BAR, Freitas T. Rice Insect Pests and their Management. Burleigh Dodds Science Publishing Limited, Cambridge, UK; 2017 (In press).
13. Litsinger JA, Barrion AT, Soekarna D. Upland rice insect pests: their ecology, importance and control. IRRI Research Paper Series 1987;123:1–41.
14. Pathak MD. Ecology of common insect pests of rice. Annual Review of Entomology 1968;13:257–94.
15. Togola A, Nwilene FE, Agbaka A, Degila F, Tolulope A, Chougourou D. Screening upland varieties of NERICA and its parents for resistance to stalk-eyed fly, *Diopsis* sp. (Diptera, Diopsidae) in Benin. Journal of Applied Sciences 2011;11:145–50.
16. E.A. Akinsola. Present status of different rice stem stem borers in plants of Nigeria. Rice Entomology Newsletter; 1975. p. 3.
17. Akinsola EA. The biology and ecology of rice stem borers in Nigeria. PhD thesis, University of Ibadan, Nigeria; 1979.
18. Alam MS. Seasonal abundance of rice stem borer species in upland and irrigated rice in Nigeria. Insect Science and its Application 1988;9:191–5.
19. Alam MS, John VT, Zan K. Insect pests and diseases of rice in Africa. In: Zan K, Garrity DP, Zimdahl A, editors. Rice Improvement in Eastern, Central and Southern Africa. International Rice Research Institute, Manila, Philippines; 1985. p. 67–82.
20. Hely PC. Insect pests of the rice crop. The Agricultural Gazette of New South Wales 1958;69:29–32.
21. Lv J, Wilson LT, Longnecker MT. Tolerance and compensatory response of rice to sugarcane borer (Lepidoptera: Cambidae) injury. Environmental Entomology 2008;37:796–807.
22. Pathak MD. Insect Pests of Rice. The international Rice Research Institute, Los Baños, Philippines; 1975.
23. Ogah EO, Nwilene FE. A review of the biology and ecology of the African rice gall midge *Orseolia oryzivora* (Diptera: Cecidomyiidae). Plant Protection Quarterly 2014;29:16–9.
24. Heinrichs EA, Barrion AT. Rice-Feeding Insects and Selected Natural Enemies in West Africa: Biology, Ecology, Identifcation. International Rice Research Institute, Los Baños, Philippines and WARDA-The Africa Rice Center and Abidjan, Côte d'Ivoire; 2004. 242 pp.
25. Dale D. Insect pestsof the rice plant – their biology and ecology. In: Heinrichs EA, editor. Biology and Management of Rice Insects. Wiley Eastern, New Delhi. 1994; p. 363–485.
26. Heinrichs EA. Control of leafhopper and planthopper vectors of rice viruses. In: Maramorosch K, Harris KF, editors. Leafhopper Vectors of Plant Disease Agents. Academic Press, New York; 1979. p. 529–60.
27. Cabauatan PQ, Cabunagan RC, Choi IL-R. Rice viruses transmitted by the brown planthopper *Nilaparvata lugens* Stål.

In: Heong KL, Hardy B, editors. Planthoppers: New Threats to the Sustainability of Intensive Rice Production Systems in Asia. International Rice Research Institute, Los Baños, Philippines; 2009. p. 357–68.

28. Lv J, Zhu ZR, Lou YG, Cheng JA. Review of research into outbreaks and management of rice planthoppers. Chinese Journal of Applied Entomology 2013;50:565–74.
29. Heinrichs EA, Mochida O. From secondary to major pest status: the case of insecticide-induced rice brown planthopper, *Nilaparvata lugens*, resurgence. Protection Ecology 1984;7:201–18.
30. King ABS, Saunders JL. The Invertebrate Pests of Annual Food Crops in Central America. A Guide to their Recognition and Control. Overseas Development Administration, London; 1984.
31. Morales FJ, Jennings PR. Rice hoja blanca: a complex plant-virus-vector pathosystem. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition, and Natural Resources. CABI Publishing, Wallingford, UK; 2010. vol. 5, no. 043.
32. dela Cruz CG. Host plant range of *Nisia atrrovenosa*. International Rice Research Newsletter 1986;11(2):26–7.
33. CABI. 2016. *Nisia nervosa* (gray planthopper) Invasive Species Compendium. Avaliable from: URL:http:// www.cabi.org/isc/datasheet/36348.
34. Wilson MR, Claridge MF. Handbook for the Identification of Leafhoppers and Planthoppers of Rice. Centre for Agriculture and Biosciences International, Wallingford, UK; 1991.
35. Huang PK, Qi SC. A list of insect pests of rice of Fujian province, China. Wuyi Science Journal 1981;1:79–92.
36. Koudamiloro A, Nwilene FE, Togola A, Akogbeto M. Insect vectors of rice yellow mottle virus. Journal of Insects 2015;2015(72175112):1–12.
37. Akingbohungbe AE. Nomenclatural problems, biology, host plant and possible vector status of Auchenorryncha associated with crop plants in Nigeria. In: Knight WJ, Pant NC, Robertson TS, Wilson MR, editors. Proceedings of the 1st International Workshop on Leafhoppers and Planthoppers of Economic Importance. Commonwealth Institute of Entomology, London; 1983. p. 365–70.
38. Nwilene FE, Traore AK, Asidi AN, Sere Y, Onasanya A, Abo ME. New records of insect vectors of rice yellow mottle virus (RYMV) in Côte d'Ivoire, West Africa. Journal of Entomology 2009;6(4):189–97.
39. Kramer JP. New Liberian leafhopper of the genus *Recilia* (Homoptera: Cicadellidae: Deltocephalinae). Proceedings of the Biological Society of London 1962;75:259–68.
40. Zakra AN, Pomier M, de Taffin G. Initial results of an intercropping experiment of coconut with food crops in the Middle Côte d'Ivoire. Oléagineux 1986;41:381–9.
41. Alam MS. Whitefly (Hemiptera: Aleyrodidae) – a potential pest of rice in West Africa. International Rice Research Newsletter 1989;114(3):38–9.
42. Kumar P. Survey on the incidence of pests of rice under rainfed lowland ecosystem. Karnataka Journal Agricultural Science 2003;16:460.
43. Donayre DKM, Endino CA, Seville CU, Cicon IMG. Predominant pests and pest management practices of rainfed rice farmers in Negros Island, Philippines. Asia Life Sciences 2014;23(2):497–513.
44. Litsinger JA, Barrion AT, Canapi BL, Lumaban MD, Pantua PC, Aquino GB. The rice whorl maggot, *Hydrellia philippina* Ferino (Diptera: Ephydridae) in the Philippines: a review. Philippines Entomologist 2013;27(1):1–57
45. Banwo OO, Makundi RH, Abdallah RS, Mbapila JC. Newly recorded species of *Chaetocnema*, vector of rice yellow mottle virus in Tanzania. New Zealand Journal of Crop and Horticultural Science 2001;29:61–5.
46. Islam Z, Catling D. Rice Pests of Bangladesh: Their Ecology and Management. The University Press, Ltd., Dhaka, Bangladesh; 2012. 422p
47. Reddy PR. Kresek phase of bacterial blight of rice. Oryza 1984;21:179–87.
48. Ramasamy CJ, Jatileksono T. Inter-country comparison of insect and disease losses. In: Evenson RE, Herdt RW, Hussain M, editors. Rice Research in Asia: Progress and Priorities. CABI Publications and IRRI, Wallingford, UK. Manila, Philippines; 1996. p. 305–16.
49. Azzam O, Chancellor TCB. The biology, epidemiology, and management of rice tungro disease in Asia. Plant Disiease 2002;86:88–100.
50. Dasgupta I. Rice tungro. In: Tennant P, Fermin G, editors. Virus Diseases of Tropical Crops. CABI, Wallingford, UK; 2015. p. 202–15.
51. Ling KC, Tiongco ER. Transmission of rice tungro virus at various temperatures: a transitory virus-vector interaction. In: Maramorosch K, Harriseds KF, editors. Leafhopper Vectors and Plant Disease Agents. Academic Press, New York; 1979. p. 349–66.
52. Hibino H. Rice ragged stunt, a new virus disease occurring in tropical Asia. Review of Plant Protection Research 1979;12:98–110.
53. Hibino H. Insect-borne viruses in rice. In: Harris KF, editor. Advances in Disease Vector Research. Springer-Verlag, New York; 1989. vol. 6, p. 209–41.
54. Hibino H. Biology and epidemiology of rice viruses. Annual Review of Phytopathology 1996;34:249–74.
55. Morales FJ, Niessen AI. Association of spiral filamentous viruslike particles with rice hoja blanca. Phytopathology 1983;73:971–4.
56. des Vignes W. Literature review on *Sogatodes* (*Sogata oryzicola*) (Muir) and *Sogatodes cubanus* (Crawford) (Homoptera: Delphacidae) vectors of Hoja Blanca virus (HBV) pf rice. Journal of the Agricultural Society of Trinidad and Tobago 1987;87:59–62.
57. Jennings PR, Rosero MJ, Burgos LJ. Hoja blanca del arroz. Agricultura Tropical 1958;14:511–6.
58. Lamey HA. Varietal resistance to hoja blanca. In: International Rice Research Institute, editor. The Virus Diseases of the Rice Plant. John Hopkins University Press, Baltimore, MD; 1969; p. 293–311.
59. Everett TR, Lamey HA. Hoja blanca. In: Maramorosch K, editor. Viruses, Vectors and Vegetation. Interscience, New York; 1969. p. 361–77.
60. Fomba SN. Rice yellow mottle virus (RYMV) on swamp rice in Guinea. International Rice Research Newsletter 1990;15(6):21.

61. Awoderu VA, Alam MS, Thottapilly G, Alluri K. Outbreaks and new records. Ivory Coast. Rice yellow mottle virus in upland rice. FAO Plant Protection Bulletin 1987;35(1):32–3.

62. IRRI (International Rice Research Institute). Field Problems of Tropical Rice. Revised. IRRI, Manila, Philippines, 1983.

63. Reckhaus PM, Andriamasintseheno HF. Rice yellow mottle virus in Madagascar and its epidemiology in the northwest of the Island. Z. Pflanzenkr. Pflanzenschutz 1997;104:289–95.

64. Koudamiloro A, Nwilene FE, Silue D, Togola A, Oyetunji O, Sere Y, *et al.*Identification of insect vectors of *Rice yellow mottle virus* (RYMV) in Benin. Journal of Entomology 2014;11:153–62.

65. Baldacci E, Amici A, Belli G, Corbelta G. Il giallume del riso: osservazioni e ricerche su sintomatologia, epidemiologia ed eziologia [English summary]. Il Riso 1970;19:3–9.

66. Handoo ZA. Plant-parasitic nematodes. 1998. Available from: URL: https://www.ars.usda.gov/northeast-area/beltsville-md/beltsville-agricultural-research-center/nematology-laboratory/docs/plant-parasitic-nematodes/ (accessed on 23 March 2017).

67. Mantelin S, Bellafiore S, Kyndt T. *Meloidogyne graminicola*: a major threat to rice agriculture. Molecular Plant Pathology 2017;18:55–66.

68. Neog PP, Chauhan MK. Incidence and management of ufra disease caused by *Ditylenchus* angustuus in deepwater rice in Assam. Annals Plant Protection Sciences 2015;23:189–90.

69. Bridge J, Luc M, Plowright RA. 1990. Nematode parasites of rice. In: Luc M, Sikora RA, Bridge J, editors. Plant Parasitic Nematodes in Subtropical and Tropical Agriculture. CAB International, Wallingford, UK; 1990. p. 69–108.

70. CAB International. *Ditylenchus angustus*. In: Crop Protection Compendium, Global Module. 3rd ed. CAB International, Wallingford, UK; 2001. Available from: URL: http://www.cabi.org/isc/datasheet/19285.

71. Prot J-C, Rahman ML. Nematode ecology, economic importance, and management in rice ecosystems in South and Southeast Asia. In: Teng PS, Heong KL, Moody K, editors. Rice Pest Science and Management. IRRI, Los Baños, Philippines; 1994. p. 129–44.

72. Bridge J, Page SL. The rice root-knot nematode, *Meloidogyne graminicola*, on deep water rice (*Oryza sativa* subsp. *indica*). Revue de Nématologie 1982;5:225–32.

73. Plowright RA, Bridge J. Effect of *Meloidogyne graminicola* (Nematoda) on the establishment, growth and yield of rice cv. IR36. Nematologica 1990;36:81–9.

74. Soriano IRS, Schmit V, Brar DS, Prot J-C, Reversat G. Resistance to rice root-knot nematode *Meloidogyne graminicola* identified in *Oryza longistaminata* and *O. glaberrima*. Nematology 1999;1:395–8.

75. Bridge J, Plowright RA, Peng D. Nematode parasites of rice. In: Luc M, Sikora RA, Bridge J, editors. Plant Parasitic Nematodes in Subtropical and Tropical Agriculture. 2nd ed. CABI Publishing; 2005. Organic-Research.com, CABI Bioscience, Egham, UK.

76. Taylor DP. Parasitism of banana by *Heterodera oryzae*. Revue de Nématologie 1978;1:165–9.

77. Charles JS, Venkitesan T. New hosts of *Helerodera oryzicola* Rao & Jayaprakash, 1978, in Kerala, India. Indian Journal of Nematology 1984;14:181–2.

78. Jayaprakash A, Rao YS. Hatching behavior of the cyst nematode, *Heterodera oryzicola*. Indian Journal of Nematology. 1982;12:400–2.

79. Fortuner R, Merny G. Root parasitic nematodes of rice. Revue de Nematologie 1979;2:79–102.

80. Jayaprakash A, Rao YS. Effect of *Heterodera oryzicola* incidence on growth of rice. Oryza 1982;19:60–1.

81. Singleton GR, Belmain S, Brown PR, Aplin K, Htwe NM. Impacts of rodent outbreaks on food security in Asia. Wildlife Research 2010;37:355–59.

82. Khan A. Bio-economic impacts of vertebrate pests on crops with special reference to rodent pests in Pakistan and other countries. Proceedings of Pakistan Congress of Zoology, 2013:33:75–108.

83. Shiels AB, Pitt WC, Sugihara RT, Wittmer GW. Biology and impacts of Pacific Island invasive species. II. *Rattus rattus*, the black rat (Rodentia: Muridae). Pacific Science 2014;68(2):145–84.

84. Yosida TH. Cytogenetics of the Black Rat. Karyotype Evolution and Species Differentiation. University of Tokyo Press, Tokyo, 1980.

85. Barrett SCH, Seaman DE. The weed flora of Californian rice fields. Aquatic Botany 1980;9:351–76.

86. Moody K. Weeds Reported in rice in South and Southeast Asia. International Rice Research Institute, Manila, Philippines, 1989.

87. Ampong-Nyarko K, De Datta SK. Effects of light and nitrogen and their interaction on the dynamics of rice-weed competition. Weed Research 1993;33:1–8.

88. Arunvenkatesh S, Kumar RV, Rajasekar M. Climate change and rice (*Oryza sativa* L.) production. Asian Journal of Environmental Sciences 2016;11:111–17.

89. Woodward FI, Cramer W. Plant functional types and climatic changes: introduction. Journal of Vegetation Science 1996;76:306–8.

90. Ramachandiran K, Balasubramanian R. Weedy rice and its management – a review. Agricultural Reviews 2012;33:175–9.

91. Benvenuti S. Weed movement and dispersal strategies in the agricultural environment. Weed Biology and Management 2007;7:141–57.

92. Labrada R. The need for improved weed management in rice. FAO Document Repository. 2003. Available from: URL: http://www.fao.org/docrep/006/y4751e/y4751e0l.htm (accessed 27 February 2017).

93. Zhang ZP. Weed management in rice in China. Summary presented at FAO Workshop on *Echinochloa* spp. Control. Beijing, China, 27 May 2001.

94. Abeysekera SW, Anuruddhika SK. Management of *Echinochloa* spp. in rice in Sri Lanka. Paper presented at the FAO workshop on *Echinochloa* spp. control, Beijing, China; 2001. 13 pp.

95. Rodenburg J, Demont M, Zwart SJ, Bastiaans L. Parasitic weed incidence and related economic losses in rice in Africa. Agriculture, Ecosystems & Environment 2016;235:306–17.

96. Schoenly KG, Cohen JE, Heong KL, Arida GS, Barrion AT, Litsinger JA. Quantifying the impact of insecticides on food web structure of rice-arthropod populations in a Philippine farmer's irrigated field: a case study. In: Polis GA,

Winemiller KO, editors. Food Webs: Integration of Patterns and Dynamics. Chapman and Hall, New York; 1996. p. 343–351.

97. Wilby A, Lan LP, Heong KL, Huyen NPD, Quang NH, Minh NV, *et al.* Arthropod diversity and community structure in relation to land use in the Mekong delta, Vietnam. Ecosystems 2006;9:538–49.

98. Heong KL, Schoenly K. Impact of insecticides on herbivore-natural enemy communities in tropical ecosystems. In: Haskell PT, McEwen P, editors. Ecotoxicology: Pesticides and Beneficial Organisms. Chapman and Hall, London; 1998. p. 381–403.

99. Settle WH, Ariawan H, Astuti ET, Cahyana W, Hakim AL, Hindayana D, *et al.* Managing tropical rice pests through conservation of generalist natural enemies and alternative prey. Ecology 1996;77:1975–88.

100. Way MJ, Heong KL. The role of biodiversity in the dynamics and management of insect pests of tropical irrigated rice: a review. Bulletin of Entomological Research 1994;84:567–87.

101. Wyss E, Luka H, Pfiffner L, Schlatter C, Uehlinger G, Daniel C. Approaches to pest management in organic agriculture: a case study in European apple orchards. Organic Research 2005; (May):33N–6N. CAB International.

102. Zehnder G, Gurr GM, Kuehne S, Wade MR, Wratten SD, Wyss E. Arthropod pest management in organic crops. Annual Review of Entomology 2006;52:57–80.

103. Litsinger JA. Cultural, mechanical, and physical control of rice insects. In: Heinrichs EA, editor. Biology and Management of Rice Insects. Wiley Eastern, New Delhi, India; 1994. p. 549–84.

104. Fujita D, Kohli A, Horgan FG. Rice resistance to planthoppers and leafhoppers. Critical Reviews in Plant Sciences 2013;32:162–91.

105. Jena KK, Kim S-M. Current status of brown planthopper resistance and genetics. Rice 2010;3:161–71.

106. Heinrichs EA, Medrano FG, Rapusas HR. Genetic Evaluation for Insect Resistance in Rice. IRRI, Los Baños, Philippnes, 1985.

107. Peng S, Khush GS. Four decades of breeding for varietal improvement ofi rrigated lowland rice in the International Rice Research Institute. Plant Production Science 2003;6(3):157–64.

108. Alam SN, Cohen MB. Durability of brown planthopper, *Nilaparvata lugens*, resistance in rice variety IR64 in green-house selection studies. Entomologia Experimentalis et Applicata 1998;89:71–8.

109. Mundt CC. Durable resistance: a key to sustainable management of pathogens and pests. Infection, Genetics and Evolution 2014;27:446–55.

110. Crill P, Ham YS, Beachell HM. The rice blast disease in Korea and its control with race prediction and gene rotation. Korean Journal of Breeding Science 1981;13:106–14.

111. Zhu Y, Chen H, Fan J, Wang Y, Li Y, Chen J, *et al.* Genetic diversity and disease control in rice. Nature 2000;406:718–22.

112. Fujita D, Yoshimura A, Yasui H. Development of near-isogenic lines and pyramided lines carrying resistance genes to green rice leafhopper (*Nephotettix cincticeps* Uhler) with the Taichung 65 genetic background in rice (*Oryza sativa* L.). Breeding Science 2010;60:18–27.

113. Hu J, Li X, Wu C, Yang C, Hua H, Gao G, *et al.* Pyramiding and evaluation of the brown planthopper resistance genes Bph14 and Bph15 in hybrid rice. Molecular Breeding 2012;1:61–9.

114. Qiu Y, Guo J, Jing S, Zhu L, He G. Development and characterization of japonica rice lines carrying the brown planthopper-resistance gene BPH12 and BPH6. Theoretical and Applied Genetics 2012;124:485–94.

115. Sharma PN, Torii A, Takumi S, Mori N, Nakamura C. Marker assisted pyramiding of brown planthopper (*Nilaparvata lugens*) resistance genes Bph1 and bph2 on rice chromosome 12. Hereditas 2004;140:61–9.

116. Ge L-Q, Wan D-J, Xu J, Jiang L-B, Wu J-C. Effects of nitrogen fertilizer and magnesium manipulation on the *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae). Journal of Economic Entomology 2013;106:196–205.

117. De Kraker J, Rabbinge R, Van Huis A, Van Lenteren JC, Heong KL. Impact of nitrogenous fertilization on the population dynamics and natural control of rice leaffolder. (Lep.: Pyralidae). International Journal of Pest Management 2000;46:225–35.

118. Chantaraprapha N, Ratanyukui W, Semapetch U, Seetanun W. Influence of ammonium phosphate levels on rice leaf roller incidence. International Rice Research Newsletter 1980;5:21.

119. Swaminathan K, Saroja R, Raju N. Influence of source and level of nitrogen application on pest incidence. International Rice Research Newsletter 1985;10:24.

120. Lu ZX, Heong KL, Yu XP, Hu C. Effects of plant nitrogen on ecological fitness of the brown planthopper, *Nilaparvata lugens* in rice. Journal of Asia-Pacific Entomology 2004;7:97–104.

121. Jiang MX, Cheng JA. Interactions between the striped stem borer *Chilo suppressalis* (Walk.) (Lep., Pyralidae) larvae and rice plants in response to nitrogen fertilization. Journal of Pest Science 2003;76:124–8.

122. Hou M, Han Y. Silicon-mediated rice plant resistance to the Asiatic rice borer (Lepidoptera: Crambidae): Effects of silicon amendment and rice varietal resistance. Journal of Economic Entomology 2010;103:1412–9.

123. Ranganathan S, Suvarchala V, Rajesh YBRD, Srinivasa Prasad M, Padmakumari AP, Violeti SR. Effects of silicon sources on its deposition, chlorophyll content, and disease and pest resistance in rice. Biologia Plantarum 2006;50:713–6.

124. Hosseini SZ, Jelodar NB, Bagheri N. Study of silicon effects on plant growth and resistance to stem borer in rice. Communications in Soil Science and Plant Analysis 2012;43:2744–51.

125. Djamin A, Pathak MD. Role of silica in resistance to Asiatic rice borer, *Chilo suppressalis* (Walker), in rice varieties. Journal of Economic Entomology 1967;60:347–51.

126. Heinrichs EA, Medrano FG. Influence of fertilizer on the population development of brown planthopper (BPH). International Rice Research Newsletter 1985;10(6):20–1.

127. Kajimura T, Fujisaki K, Nakasuji F. Effect of organic rice farming on leafhoppers and planthoppers: 2. Amino acid content in the rice phloem sap and survival rate of planthoppers. Applied Entomology and Zoology 1995;30:17–22.

128. Kajimura T, Widiarta IN, Nagai K, Fujisaki K, Nakasuji F. Effect of organic rice farming on planthoppers: 4. Reproduction of the white backed planthopper, *Sogatella furcifera* Horváth

(Homoptera: Delphacidae). Research on Population Ecology 1995;37:219–24.

129. Sogawa K. The rice brown planthopper: feeding physiology and host plant interactions. Annual Review of Entomology 1982;27:49–73.

130. Sogawa K, Pathak MD. Mechanisms of brown planthopper (Hemiptera: Delphacidae) resistance in mudgo variety of rice. Applied Entomology and Zoology 1970;5:145–58.

131. Shigematsu Y, Murofushi N, Ito K, Kaneda C, Kawabe S, Takahashi N. Sterols and asparagines in the rice plant, endogenousfactors related to resistance against the brown planthopper (*Nilaparvata lugens*). Agricultural and Biological Chemistry 1982;46:2877–9.

132. Preap V, Zalucki MP, Jahn GC, Nesbitt HJ. Effectiveness of brown planthopper predators: population suppression by two species of spider, *Pardosa pseudoannulata* (Araneae, Lycosidae) and *Araneus inustus* (Araneae, Araneidae). Journal of Asia-Pacific Entomology 2001;4:187–93.

133. Sigsgaard L. 2002. Early season natural biological control of insect pests in rice by spiders – and some factors in the management of the cropping system that may affect this control. In: Toft S, Scharff N, Henriksen PG, editors. Proceedings of the 19th European Colloquium of Arachnology, Denmark, on 17–22 July 2000. European Society of Arachnology, Bern, Switzerland; 2000. p. 57–64.

134. Rubia-Sanchez EG, Nurhasyim D, Heong KL, Zalucki M, Norton GA. White stem borer damage and grain yield in irrigated rice in West Java, Indonesia. Crop Protection 1997;16:665–71.

135. Nakasuji F, Dyck VA. Evaluation of the role of *Microvelia douglasi atrolineata* (Bergroth) (Heteroptera: Veliidae) as predator of the brown planthopper *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae). Research on Population Ecology 1984;26:134–49.

136. Reyes TM, Gabriel BP. The life history and consumption habits of *Cyrtorhinus lividipennis* Reuter (Hemiptera: Miridae). Philippines Entomologist 1975;3:79–88.

137. Gurr GM, Liu J, Read DMY, Catindig JLA, Cheng JA, Lan LP, *et al.*Parasitoids of Asian rice planthopper (Hemiptera: Delphacidae) pests and prospects for enhancing biological control by ecological engineering. Annals of Applied Biology 2011;158:149–76.

138. Landis DA, Wratten SD, Gurr GM. Habitat management to conserve natural enemies of arthropod pests in agriculture. Annual Review of Entomology 2000;45:175–201.

139. Choi SY, Lee HR, Ryu JK. Effects of carbofuran root-zone placement on the spider populations in the paddy fields. Korean Journal of Plant Protection 1978;17:99–103.

140. Fagan WF, Hakin AL, Ariawan H, Yuliyantiningsih S. Interactions between biological control efforts and insecticide applications in tropical rice agroecosystems: the potential role of intraguild predation. Biological Control 1998;13:121–6.

141. Chelliah C, Fabellar LT, Heinrichs EA. Effect of sub-lethal doses of three insecticides on the reproductive rate of the brown planthopper, *Nilaparvata lugens*, on rice. Environmental Entomology 1980;9:778–80.

142. Chelliah S, Heinrichs EA. Factors affecting insecticide induced resurgence of the brown planthopper. Environmental Entomology 1980;9:773–7.

143. Azzam S, Wang F, Wu JC, Shen J, Wang LP, Yang GQ, *et al.* Comparisons of stimulatory effects of a series of concentrations of four insecticides on reproduction in the rice brown planthopper, *Nilaparvata lugens* Stål (Homoptera: Delphacidae). International Journal of Pest Management 2009;55:347–58.

144. Bao H, Liu S, Gu J, Wang X, Liang X, Liu Z. Sublethal effects of four insecticides on the reproduction and wing formation of brown planthopper, *Nilaparvata lugens*. Pest Management Science 2008;65:170–4.

145. Hu J-H, Wu J-C, Yin J-L, Gu H-N. Physiology of insecticide-induced stimulation of reproduction in the rice brown planthopper (*Nilaparvata lugens* (Stal)): Dynamics of protein in fat body and ovary. International Journal of Pest Management 2010;56:23–30.

146. Ling S, Zhang J, Hu L, Zhang R. Effect of fipronil on the reproduction, feeding and relative fitness of brown planthopper, *Nilaparvata lugens*. Applied Entomology and Zoology 2009;44:543–8.

147. Ling S, Zhang H, Zhang R. Effect of fenvalerate on the reproduction and fitness costs of the brown planthopper, *Nilaparvata lugens* and its resistance mechanism. Pesticide Biochemistry and Physiology 2011;101:148–53.

148. Suri KS, Singh G. Insecticide-induced resurgence of the whitebacked planthopper *Sogtella furcifera* (Horvath) (Hemiptera: Delphacidae) on rice varieties with different levels of resistance. Crop Protection 2011;30:118–24.

149. Heinrichs EA, Reissig WH, Valencia S, Chelliah S. Rates and effect of resurgence-inducing insecticides on populations of *Nilaparvata lugens* (Homoptera: Delphacidae) and its predators. Environmental Entomology 1982;11:1269–73.

150. Heong KL, Escalada MM, Mai V. An analysis of insecticide use in rice: case studies in the Philippines and Vietnam. International Journal of Pest Management 1994;40:173–8.

151. Graf B, Lamb R, Heong KL, Fabellar LT. A simulation model for the population dynamics of rice leaffolders (Lepidoptera: Pyralidae) and their interactions with rice. Journal of Applied Ecology 1992;29:558–70.

152. Heong KL, Escalada MM, Huan NH, Mai V. Use of communication media in changing rice farmers' pest management in the Mekong Delta, Vietnam. Crop Protection 1998;17:413–25.

153. Huan NH, Mai V, Escalada MM, Heong KL. Changes in rice farmers' pest management in the Mekong Delta, Vietnam. Crop Protection 1999;18:557–63.

154. Heong KL, Escalada MM, Huan NH, Ky Ba VH, Quynh PV, Thiet LV, *et al.* Entertainment-education and rice pest management: a radio soap opera in Vietnam. Crop Protection 2008;27:1392–7.

155. Fabellar LT, Heinrichs EA. Relative toxicity of insecticides to rice planthoppers and leafhoppers and their predators. Crop Protection 1986;5:254–8.

156. Preetha G, Stanley J, Suresh S, Kuttalam S, Samiyappan R. Toxicity of selected insecticides to *Trichogramma chilonis*: assessing their safety in the rice ecosystem. Phytoparasitica 2009;37:209–15.

157. Preetha G, Stanley J, Suresh S, Samiyappan R. Risk assessment of insecticides used in rice on mirid bug, *Cyrthorhinus lividipennis* Reuter, the important predator of brown planthopper, *Nilaparvata lugens* (Stål). Chemosphere 2010;80:498–503.

158. Takahashi Y, Kiritani K. The selective toxicity of insecticides against insect pests of rice and their natural enemies. Applied Entomology and Zoology 1973;8:220–6.

159. Tanaka K, Endo S, Kazano H. Toxicity of insecticides to predators of rice planthoppers: spiders, the mirid bug and the drynid wasp. Applied Entomology and Zoology 2000;35:177–87.

160. Wang HY, Yang Y, Su JY, Shen JL, Gao FC, Zhu YX. Assessment of the impact of insecticides on *Anagrus nilaparvate* (Pang et Wang) (Hymenoptera: Mymaridae), an egg parasitoid of the rice planthopper, *Nilaparvata lugens* (Hemiptera: Delphacidae). Crop Protection 2008;27:514–22.

161. Norton GW, Heong KL, Johnson D, Savary S. Rice pest management: issues and opportunities. In: Pandey S, Byerlee D, Dawe D, Dobermann A, Mohanty S, Rozelle S, Hardy B, editors. Rice in the Global Economy: Strategic Research and Policy Issues for Food Security. IRRI, Los Baños, Philippines; 2010. p. 297–332.

162. Letourneau DK, Armbrecht I, Rivera BS, Lerma JM, Carmona EJ, Daza MC, *et al.*Does plant diversity benefit agroecosystems? A synthetic review. Ecological Applications 2011;21:9–21.

163. Gurr GM, Read DMY, Catindig JL, Cheng J, Liu J, Lan LP, *et al.* Parasitoids of the rice leaffolder *Cnaphalocrocis medinalis* and prospects for enhancing biological control with nectar plants. Agricultural and Forest Entomology 2012;14:1–12.

164. Gurr GM, Lu Z, Zheng X, Xu H, Zhu P, Chen G, *et al.* Multi-country evidence that crop diversification promotes ecological intensification of agriculture. Nature Plants 2016;2(3): Article no.16014. p. 1–4. DOI: 10.1038/nplants.2016.14.

165. Zhu PY, Gurr GM, Lu ZX, Heong KL, Chen GH, Zheng XS, *et al.* Laboratory screening supports the selection of sesame (*Sesamum indicum*) to enhance *Anagrus* spp. parasitoids (Hymenoptera: Mymaridae) of rice planthoppers. Biological Control 2013;64:83–9.

166. Zhu P, Wang G, Zheng X, Tian J, Lu Z, Heong KL, *et al.* Selective enhancement of parasitoids of rice Lepidoptera pests by sesame (*Sesamum indicum*) flowers. BioControl 2015;60:157–67.

167. Lu ZX, Zhu PY, Gurr GM, Zheng XS, Read DMY, Heong KL, *et al.* Mechanisms for flowering plants to benefit arthropod natural enemies of insect pests: prospects for enhanced use in agriculture. Insect Science 2014;21:1–12.

168. Lundgren JG. Relationships of Natural Enemies and Non-prey Foods. Springer International, Netherlands; 2009. 365 pp.

169. Zhu PY, Sheng XQ, Fang DH, Chen GH, Lu ZX. Effect of feeding parental adults withplant flowers on growth and predatory capacity of next generation of mirid bug *Cyrtorhinus lividipennis*. China Plant Protection 2013;3(10):17–21.

170. Rombach MC, Rombach GM, Roberts DW. Pathogens of insect pests of rice: a bibliography. Insect Science and its Application 1987;8:197–210.

171. Aguda RM, Rombach MC, Im DJ, Shepard BM. Suppression of populations of the brown planthopper, *Nilaparvata lugens* (Stål) (Hom.: Delphacidae) in field cages by entomogenous fungi (Deuteromycotina) on rice in Korea. Journal of Applied Entomology 1987;104:167–72.

172. Jin SF, Feng MG, Chen JQ. Selection of global Metarhizium isolates for the control of the rice pest *Nilaparvata lugens* (Homoptera: Delphacidae). Pest Management Science 2008;64:1008–14.

173. Jin SF, Feng MG, Ying SH, Mu WJ, Chen JQ. Evaluation of alternative rice planthopper control by the combined action of oil-formulated *Metarhizium anisopliae* and low-rate buprofezin. Pest Management Science 2010;67:36–43.

174. Li MY, Lin HF, Li SG, Xu AM, Feng MF. Efficiency of entomopathogenic fungi in the control of effs of the brown planthopper *Nilaparvata lugens* Stål (Homoptera: Delphacidae). African Journal of Microbiology Research 2012;6:7162–7.

175. Li MY, Lin HF, Li SG, Chen PR, Jin L, Yang J. Virulence of entomopathogenic fungi to adults and eggs of *Nilaparvata lugens* Stål (Homoptera: Delphacidae). African Journal of Agricultural Research 2012;7:2183–90.

176. Rombach MC, Aguda RM, Picard L, Roberts DW. Arrested feeding by the Asiatic rice borer (Lepidoptera: Pyralidae) by *Bacillus thuringiensis*. Journal of Economic Entomology 1989;82:416–9.

177. Way MO. Rice arthropod pests and their management in the United States. In: Smith CW, Dilday RH, editors. Rice: Origin, History, Technology, and Production. John Wiley & Sons, Hoboken, New Jersey; 2003. p. 437–56.

178. Rombach MC, Aguda RM, Shepard BNM, Roberts DW. Infection of the rice brown planthoper, *Nilaparvata lugens* (Homoptera: Delphacidae) by field application of entomopathogenic Hyphomycetes (Deuteromycotina). Environmental Entomology 1986;15:1070–73.

179. Su J, Wang Z, Zhang K, Tian X, Tin Y, Zhao X, *et al.* Status of insecticide resistance of the whitebacked planthopper, *Sogatella furcifera* (Hemiptera: Delphacidae). Florida Entomologist 2013;96:948–56.

180. Matsumura M, Sanada-Morimura S. Recent status of insecticide resistance in Asian rice planthoppers. Japan Agricultural Research Quarterly Journal 2010;44:225–30.

181. Stern VM, Smith RF, Van Den Bosch R, Hagen KS. The integrated control concept. Hilgardia 1959;29:81–101.

182. Bautista RC, Heinrichs EA, Rejesus RS. Economic injury levels for the rice leaffolder *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae): insect infestation and artificial leaf removal. Environmental Entomology 1984;13:439–43.

183. Litsinger JA, Bandong JP, Canapi BL, Dela Cruz CG, Pantua PC, Alviola AL, *et al.* Evaluation of action thresholds for chronic rice insect pests in the Philippines: I. Less frequently occurring pests and overall assessment. International Journal of Pest Management 2005;51:45–61.

184. Litsinger JA, Bandong JP, Canapi BL, Dela Cruz CG, Pantua PC, Alviola AL, *et al.* Evaluation of action thresholds for chronic rice insect pests in the Philippines: II. Whorl maggot and defoliators. International Journal of Pest Management 2006;52:167–80.

185. Litsinger JA, Bandong JP, Canapi BL, Dela Cruz CG, Pantua PC, Alviola AL, *et al.* Evaluation of action thresholds for chronic rice insect pests in the Philippines: III. Leaffolders. International Journal of Pest Management 2006;52:181–94.

186. Litsinger JA, Bandong JP, Canapi BL, Dela Cruz CG, Pantua PC, Alviola AL, *et al.* Evaluation of action thresholds for chronic rice insect pests in the Philippines: IV. Stem borers. International Journal of Pest Management 2006;52:195–207.

187. Morgan DR, Tugwell NP, Bernhardt JL. Early rice field drainage for control of rice water weevil (Coleoptera: Curculionidae) and evaluation of an action threshold based upon leaf-feeding scars of adults. Journal of Economic Entomology 1989;82:1757–9.

188. Matteson PC. Insect pest management in tropical irrigated rice. Annual Review of Entomology 2000;45:549–74.

189. Reissig WH, Heinrichs EA, Valencia SL. Insecticide-induced resurgence of the brown planthopper, *Nilaparvata lugens*, on rice varieties with different levels of resistance. Environmental Entomology, 1982;11(1):165–8.

190. Reissig WH, Heinrichs EA, Valencia SL. Effects of insecticides on *Nilaparvata lugens* and its predators: spiders, *Microvelia atrolineata*, and *Cyrtorhinus lividipennis*. Environmental Entomology 1982;11(1):193–9.

191. Fabellar LT, Heinrichs EA, Rapusas H. Response to inecticides of green leafhoppers from four sites in the Philippines. International Rice Research Newsletter 1981;6(6):8.

192. Zhao X, Wu X, Wang Y, Cang T, Chen L. Assessment of toxicity risk of insecticides used in rice ecosystem on *Trichogramma japonicum*, an egg parasitoid of rice lepidopterans. Journal of Economic Entomology 2012;105:92–101.

193. Matsumura M, Takeuchi H, Satoh M, Sanada-Morimura S, Otuka A, Watanabe T, *et al.* Species-specific insecticide resistance to imidacloprid and fipronil in the rice planthoppers *Nilaparvata lugens* and *Sogatella furcifera* in East and South-east Asia. Pest Management Science 2008;64:1115–21.

194. Prakash A, Bentur JS, Prasad MS, Tanwar RK, Sharma OP, Bhagat S, *et al.* Integrated Pest Management for Rice. Directorate of Plant Protection, Qarantine & Storage, CGO Complex, NH IV, Faridibad-121004, India; 2014.

195. Van den Berg H, Jiggins J. Investing in farmers: the impacts of farmer field schools in relation to integrated pest management. World Development 2007;35:663–86.

196. Pontius JC, Dilts R, Bartlett A. Ten Years of IPM Training in Asia: From Farmer Field School to Community IPM. FAO, Bangkok, Thailand; 2002.

197. Pincus J. The impact of IPM farmer field schools on farmers' cultivation practices in their own fields. FAO Programme for Community IPM in Asia Report; 1999.

198. Tripp R, Wijeratne M, Piyadasa VH. What should we expect from farmer field schools? A Sri Lanka case study. World Development 2005;33:1705–20.

199. Rola AC, Jamias SB, Quizon JB. Do farmer field school graduates retain and share what they learn? An investigation in Iloilo, Philippines. Journal of International Agriculture and Extension Education 2002;9:65–76.

200. Quizon J, Feder G, Murgai R. Fiscal sustainability of agricultural extension: the case of the farmer field school approach. Journal of International Agriculture and Extension Education 2001;8:13–24.

201. Rejesus RM, Palis FG, Lapitan AV, Chi TTN, Hossain M. The impact of integrated pest management information dissemination methods on insecticide use and efficiency: evidence from rice producers in South Vietnam. Review of Agricultural Economics 2009;31:814–33.

202. Huan NH, Chien HV, Quynh PV, Tan PS, Du PV, Escalada MM, *et al.* Motivating rice farmers in the Meking Delta to modify pest management and related practices through mass media. International Journal of Pest Management 2008;54:339–46.

203. Huelgas ZM, Templeton D, Castanar P. Three Reductions, Three Gains (3R3G) technology in South Vietnam: searching for evidence of economic impact. Contributed paper at the 52ecknd Annual Conference of the Australian Agricultural Resource Economics Society held at Rydges Lakeside, Canberra ACT, Australia, 5–8 February 2008.