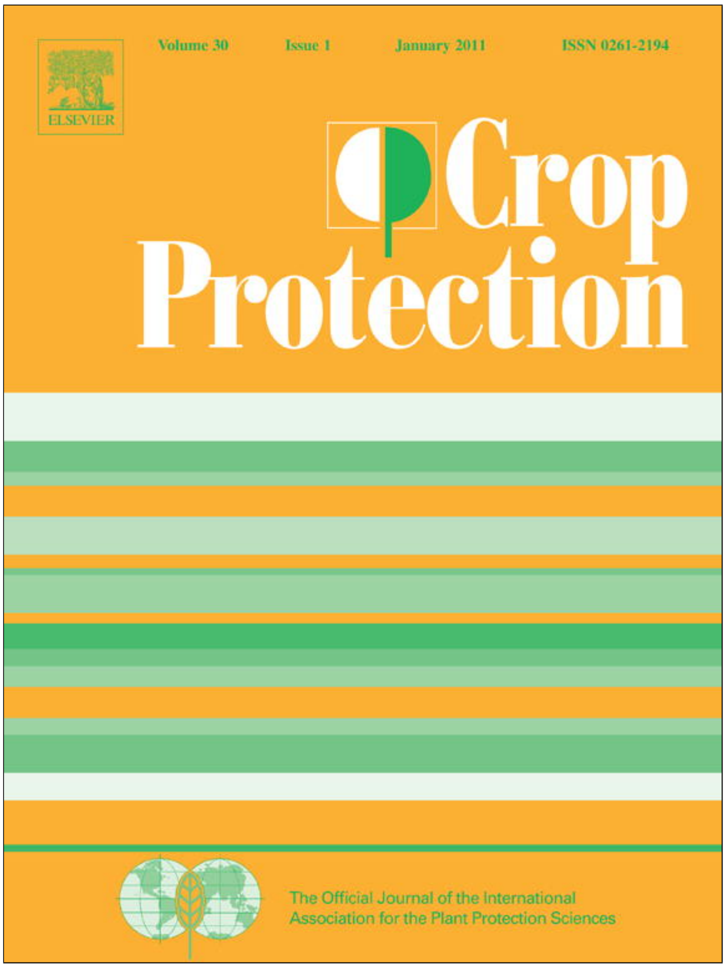
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Review

A review of principles for sustainable pest management in rice

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ABSTRACT

This review addresses four principles on which sustainable pest management in rice is to be grounded. The goal of modern pest management is to contribute to agricultural sustainability, with its different facets (food security, balanced relations between man-made and natural ecosystems, conservation of ecosystem services). The four principles are considered in turn within the classic Human - Pest - Environment - Crop framework. *Biodiversity*, as a first principle, is fundamental to the functioning of food webs. The second principle, *host plant resistance* (HPR), is a pro-poor, and an often highly efficient element that critically contributes to sustainable crop protection. HPR needs to account for the other principles in its implementation in order to sustain durable resistances over time and space. The third principle, *landscape ecology*, encompasses inter-linked levels of spatial hierarchies governing the performance of systems (pests, host plants, plant genotypic make-ups, plant and crop physiology, trophic chains, and the physical environment). The fourth principle, *hierarchies*, concerns the different levels of hierarchy in a landscape, from biological to social. This principle concerns the very fabric of human societies, which involve perceptions, knowledge, and attitudes, which translate into decision-making at several scales, from the individual farmer to policy-makers. This principle thus addresses psychological, policy, and decision-making dimensions.

In this review, all organisms that may be harmful to rice are referred to as 'pests', including pathogens and animal pests. We do not address all rice pests, but proceed through a few key examples, nor do we enter into the specifics of pest management strategies covering the range of rice production situations. This is because of the very large range of rice pests, of the corresponding diversity of rice production situations worldwide, of the unprecedented rate of diversification of rice production in response to environmental, climatic, social, and economic drivers, and lastly because plant protection in rice faces emerging crop health challenges that continually call for new solutions in new contexts. The review shows that the considered framework – Human - Pest - Environment - Crop – applies, with each of its summits having a different bearing depending on the pest considered. The review further underlines the need for basic research across a range of disciplines, with novel approaches and methods, as well as the need for connecting hierarchy levels, from farmers, to consumers, to societies, the environment, and to policies.

1. Introduction

Pest management is critical to achieve rice production in a sustainable manner (Savary et al., 2006). Rice is the most important staple food worldwide, and concerns the world's largest populations of farmers and of consumers worldwide (Zeigler and Barclay, 2008). Any progress in ensuring sustained (Wilken, 1991; Greenland, 1997) rice production thus has major global policy and political implications, especially for the poor (Hossain and Fisher, 1995; Von Braun, 2009). Any sustainable improvement in rice pest management may therefore represent a considerable advance in human well-being. Yield losses in global rice output to pests (diseases, animal pests, and weeds), range from up to 20% to at least 30% of the attainable (un-injured) yield (Oerke, 2006; Savary et al., 2000a, 2000b). The amount of absolute yield lost to pests varies strongly from one production situation to another, however (Savary et al., 2000b, 2006), a fact largely hidden by the habit of expressing losses as percentages. In absolute terms, yield losses ranging from 1.2 to 2.2 tons/ha have been estimated as a result of the *combined* effects of *median* levels of disease, insect, and weed injuries, measured over hundreds of lowland rice farmers' fields in Asia

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(Savary et al., 2000a, 2000b). On the other hand, potential yield gains of at least 10–20% of the current actual (harvested) yields may be achieved from improved pest management (Willocquet et al., 2004; Oerke, 2006). Another often neglected dimension of sustainable pest management corresponds to its externalities and the additional costs associated with human health (Rola and Pingali, 1993), with the environment (Conway and Pretty, 1991), and with the maintenance of ecosystem service (Heong et al., 2010), which, when disrupted, may lead to pest resurgence (Heong and Schoenly, 1998). If such progress could be achieved in a sustainable manner, this, in itself, would address a very large fraction of the potential world food needs in the decades to come (Zeigler and Savary, 2010).

A main purpose of this review is to highlight the difficulties – 'roadblocks' (Bentley and Andrews, 1996) – that IPM in rice has encountered. It also is to underline that a shift in addressing plant protection in rice is necessary, where research is only one component in a set of hierarchies: biological, social, and economical. This review further intends to show that, despite the considerable diversity of organisms that may be harmful to rice (rice-pest systems), a common structure of thinking exists, which can be used for furthering progress.

Low adoption and in some cases discontinuance of IPM is not due to the lack of IPM techniques, knowledge, or principles. Bentley and Andrews (1996) listed six IPM road blocks: (1) missing technical information, leading to IPM recommendations that are inappropriate to on-farm constraints, (2) weak public sector, (3) inappropriate credit and subsidies, (4) influential agrochemical companies, (5) agroecosystem complexities and (6) language barriers. Perhaps the biggest roadblock lies in the inherent organizational structure of pest control (Heong et al., 1995). In many developing or emerging countries, pest control systems are designed to operate as 'fire brigades' to seek and eradicate pests and are thus equipped with pesticides and application machines to conduct battles. The re-engineering of modern pest control organization should perhaps focus on new paradigms, where farmers are clients and the primary decision makers, and which emphasise on health and environmental conservation, in order to increase rice production with less land, labour, water and chemicals, as well as the establishment of systems to address globalization and partnerships.

Several reviews on integrated pest management (IPM) have been published over the years (Zadoks, 1989; Teng and Savary, 1992; Antle and Capalbo, 1995; Bentley et al., 1995; Kogan, 1998; Jeger, 2000; McRoberts et al., 2003), especially on rice (Shepard et al., 1991; Teng, 1991; Teng and Savary, 1993; Mew, 1991; Heong, 2000; Matteson, 2000). These reviews have addressed the definition of IPM, its applications, the contexts of its implementation, as well as bottlenecks for IPM use, development, and expansion. The purpose of this paper is not to review IPM from a general point of view. Instead, we focus on rice, and use a limited series of examples of rice diseases and insects (which for convenience we shall collectively refer to as "pests") to show how a set of concepts have had applications in rice IPM, and to indicate where progress for IPM is needed. This paper thus includes three components: (i) a brief presentation of a framework involving four key elements involved in sustainable crop protection (ii) a brief review of general principles that are needed for IPM to be successful, and (iii) the application of this framework and concepts for discussing advances in sustainable rice production and protection.

2. Goal, framework, and principles

2.1. Goal: sustainability

The ultimate goal of sustainable pest management (i.e., IPM; Stern et al., 1957) is to contribute to sustainable agriculture. As such, IPM shares many philosophical, ecological, and practical characteristics with sustainable agriculture (Wilken, 1991). The connected components of production, efficiency, stability, and resilience, which are central to sustainable agriculture in general (Fresco and Kroonenberg, 1992), are also essential to IPM. Pest management is meant to sustain yields (qualitative and quantitative); it is intended to contribute to increasing the efficiency of inputs (soil, water, energy, labour, genes, or chemicals) – whether these inputs are intended to achieve suitable attainable yield, or to reduce yield losses (and thus, prevent waste of scarce, natural and/or non-renewable resources). Pest management is also intended to stabilise agricultural performance over seasons, and so prevent exceptional crop losses to insects and diseases caused by infrequent populational events. IPM, in many respects, depends on the biological resilience of the systems for which it was developed. The value of IPM recommendations can be judged by the resilience of IPM systems to external events, whether biological (such as uncommon epidemics, outbreaks, or invasions), socio-economical (such as market shifts), or physical (such as exceptional weather conditions, or climate change).

2.2. Framework: the pest management tetrahedron

As discussed in Zadoks and Schein (1979) the four summits of the pest management tetrahedron consist of: (1) the Environment (E), (2) a Crop (C), (3) a Pest (P), and (4) Humans (H). From an epistemiological standpoint, the tetrahedron significantly departs from the original structure, the "disease triangle", first introduced by Vanderplank (1963), where only the first three elements were considered (E, C, P, the latter accounting for diseases only, and not pests in general). The addition of humans in the framework truly added another dimension to plant protection preoccupations. This is because human beings have direct effects on most Crop-Environment-Pest systems; but this is also because the new summit, H (humans), recognizes the role human beings play in man-made systems, thus paving the way for considerations on what scientists should contribute to sustainable disease (pest) management (Zadoks, 1989). It should also be emphasized that the fourth summit of the tetrahedron, H, is not limited to farmers only; it also refers to farmers' communities, social networks, agro-technology suppliers, food-chain stakeholders, research and extension, as well as policy-makers. Human beings therefore occupy a multi-dimensional and critical role in the following discussion. In this review of concepts, we make use of the pest tetrahedron (Fig. 1) as a guide, with a series of expansions.

One first element of expansion is that P, "pest" represents any harmful agent to a growing crop, with particular emphasis on insects

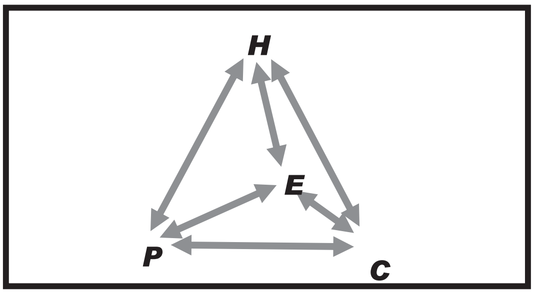

Fig. 1. The pest tetrahedron, as used in this review. H: Humans; includes individual farmers, farmers' communities, agricultural stakeholders (policies), and decisions they make. E: Environment, physical, chemical and biological; includes natural enemies, biological control agents. C: Crop; includes its attributes: genotype, host plant resistances, physiology, crop density and architecture, and the physical microenvironment in the crop. P: Pests; includes pathogens, and animals, especially insects; and vectors of pathogens, with their genetic attributes.

and pathogens. P incorporates the inherent genetic diversity of pests, and their ability to adapt to changing environments, whether physical, chemical, or biological. Throughout the review, P concentrates on individual pests. However, towards the end of this paper, P refers not to one specific pest, but to combinations of harmful organisms, that is, P refers to crop health syndromes (Savary et al., 2011).

The environment, E, is often limited in the literature to the physical environment only. For the purpose of this review, and in order to show more clearly the importance of principles through the four components of the tetrahedron, E encompasses the biological, chemical, and physical components of the environment. E thus includes components as diverse as pest natural enemies (including insect predators and parasitoids) and antagonists (including a wide range of micro-organisms in the phyllosphere and the rhizosphere), meso-climatic factors influencing root or canopy micro-climates (micro-climatic factors being considered under C, the crop component), and the chemical environment, including fungicides and insecticides.

Crop, C, incorporates elements pertaining to the host plant genetic make-up, including host plant resistance (HPR), the crop physiology, the crop phenology, and their interactions. C also incorporates microclimate factors that may influence the behaviour of crop-pest systems. This is because, while the microclimate in a crop is driven by physical meso-environment (under E), microclimate also depends on the crop structure (i.e., its density and architecture). Thus, C not only accounts for the direct effects of HPR, but also for the conditions under which HPR may operate. Furthermore, the expression of resistance depends on the physiology of the crop (predisposition; Schoeneweiss, 1975). This is of prime importance for many plant pests in general, and in particular for rice diseases (such as brown spot, leaf blast, or sheath blight) and insect pests (such as planthoppers, leafhoppers, or leaf folders).

Summit H accounts for the indirect, yet often very strong, effect of crop management on pests (Palti, 1981; Zadoks, 1993). Summit H thus includes farmers and their management decisions, strategic or tactical (Zadoks and Schein, 1979). The former are made before crop establishment, including, e.g., a crop rotation, the choice of a variety—susceptible or resistant to a pest—, or a crop establishment method. The latter are made after crop establishment, including, e.g., water and nutrient management, and of course pesticide use. This fourth element of the tetrahedron goes several scales beyond individual farmer's field actions, however: it also encompasses policies, markets, subsidies, and decisions on which farmers have little or no control. Because agricultural policies are so strongly linked with perceptions and attitudes, whether individual or collective, H also involves psychologies, as well as possible conflicting interests in different circles.

This framework allows consideration of the essential components that sustainable plant protection (IPM) must involve, and which interact through a set of key principles described in the following sections.

2.3. First principle: biodiversity

In spite of the debate on the diversity-stability theory (Murdoch, 1975; Loreau et al., 2001), biodiversity (Wilson, 1992), in its broadest possible sense, plays a key role in rice IPM (Way and Heong, 1994; Heong and Schoenly, 1998). It has been hypothesized that in most of the current Asian rice systems, the crop and its biological environment have co-evolved for such a long time that the necessary trophic networks, albeit simple, have become inherently stable (Jeger, 2000). As we discuss below, rice-based agrosystems also provide one good example where biological diversity, when suitably managed, successfully sustains agricultural performances.

Biodiversity is the foundation of ecosystem services that are fundamental to human well being (Millennium Ecosystem Assessment, 2005). With respect to insect pests, the ecosystem services that rice-based agrosystems may provide in preventing herbivores from multiplying and becoming pests are invasion resistance and pest regulation. Two, diverse, functional groups, predators and parasitoids, mainly provide these services. Rice is an ephemeral habitat lasting some 120–150 days and can be subject to herbivore species invasions after crop establishment. Predators, such as spiders, are present in the rice ecosystem even before rice is sown, as they live on detritivores and other aquatic fauna. Thus, invading herbivores such as planthoppers are vulnerable to predation upon landing. Parasitoids, especially egg parasitoids, provide a regulatory service by searching for and attacking eggs that the invading pests embed into the rice plant tillers. Eggs escaping parasitization hatch into nymphs that can be further regulated by ants, spiders, microveliids, crickets and other aquatic fauna (Settle et al., 1996; Way et al., 2002). Planthopper egg parasitization can be enhanced if habitats adjacent to rice fields are dominated by the grasses, i.e., *Bracharia mutica*, that harbour planthoppers such as *Tagosodes pasanus* and *Toya* sp. The egg parasitoid, *Anagrus* sp. attacks both the rice and non-rice planthoppers (Yu et al., 1996). The adjacent *Bracharia* rich habitats are also refuge areas for predatory crickets such as *Methioche vittaticollis* and *Anaxipha longipennis*, which eat the eggs of leaf folder invaders (De Kraker et al., 1999). Arthropod community food-chain lengths in insecticide sprayed crop stands were rapidly depressed from about 3 to 2, and they only recovered 3 weeks after the last spray (Heong and Schoenly, 1998).

Biodiversity can also be seen from the point of view of pests. For instance, in the case of insects as well as pathogens, the diversity of pests and of their life cycles can be described in terms of life strategies, including variation in reproduction strategies (typically, r and K; Zadoks and Schein, 1979), host range size, survival ability and dispersion range. These traits must be accounted for when integrated strategies for pest management are developed (Zadoks and Schein, 1979; Magarey et al., 2006).

2.4. Second principle: host plant resistance

Host Plant Resistance is a pillar for pest management in general (Kogan, 1998), and for rice in particular (Bonman et al., 1992). The group of technologies encompassed by the term Host Plant Resistance has many advantages: it is environmentally-friendly, inexpensive and thus pro-poor, and potentially very efficient (Teng, 1994a). Its efficiency however may not be durable. The durability of resistance strongly depends on the level of specificity existing between the host and pest interactions. High level of specificity (e.g., blast, gall midge) generally corresponds to (1) the existence of pest- or pathogen specific resistance genes in the host population which can be harnessed and are potentially very efficient, and (2) the possibility of the pest population to adapt to host population and overcome resistance genes generating the boom-and-burt cycle (Person, 1966; Zadoks and Schein, 1979; McDonald and Linde, 2002). The establishment of strategies for deployment of resistance genes over time and space is critical in sustaining the efficiency of these genes. Such strategies have been designed from epidemiological and ecological concepts and methods (e.g., Leonard and Fry, 1989), but are unfortunately seldom used, for lack of the required technical and policy (infra-) structures. This has recently been illustrated by recent outbreaks of the brown planthopper in Asia (Seo et al., 2009). Sustained efforts to identify new resistance genes, however, has enabled until now the use of host plant resistance to maintain pathogen and insect pests population at low level for a number of key pests, in many crops especially rice (Bonman et al., 1992).

In the case of low specificity between host and pest populations (e.g., sheath blight or polyphagous insects in rice), partial resistance, if existing, is more likely to be efficient for pest management. In rice, partial resistance to pests has been used in a very limited way until now, in spite of its likelihood to provide more durable resistance than complete resistance. This under-exploitation is mostly due to difficulties in identifying genetic sources for partial resistance, and, even more so, to incorporate these sources into breeding programs (Poland et al., 2009). The combined use of genetic and ecological approaches, mobilizing an array of tools (molecular markers, simulation models, etc) may provide avenues to generate and deploy partial resistance at large scale in the future (Srinivasachary et al., 2011).

In the case of rice insects, large scale screening to find rare resistant individuals among the rice wild species and landraces has led to the identification of resistance genes and QTLs (quantitative trait loci) that can be transferred through conventional breeding to lines with other desirable traits (yield, grain quality; Heinrichs et al., 1985; Panda and Khush, 1995).

2.5. *Third principle: landscapes*

Landscapes usually refer to the organization over space of man-made (fields) and natural or spontaneous vegetation, and the biological systems they are associated with. They are of considerable importance in rice (e.g., Way and Heong, 1994; Heong et al., 2010), in sustaining equilibria amongst harmful and non-harmful organisms interacting in rice-based systems. Landscape structure, habitat diversity, cropping patterns and crop management practices have a strong influence on biodiversity, its functioning, and the services they provide (Thies and Tscharntke, 1999). Pesticide (insecticide) use can cause major disruptions in the performances and functioning of agroecosystems, as will be shown in the examples which follow.

Landscapes can be seen at different scales (Fresco and Kroonenberg, 1992), from the individual plant, to the crop patch, to the field, and to entire ecoregions (Zadoks et al., 1995). Plant disease epidemiology, in particular, provides modelling approaches (e.g., Willocquet and Savary, 2004) and network-based concepts (Moslonka-Lefebvre et al., 2011) to understand the linkages between such levels of organization, leading to the possibility of epidemics. At different levels of spatial organization, the respective roles of the same processes may become more, or less, important, and be influenced by host plant structure and susceptibility. Typical of the effect of landscape considered at a small scale (patch to field) is the management of rice blast through host diversity (Zhu et al., 2000). Such transitions among levels of spatial organization are illustrated in the following examples.

2.6. *Fourth principle: hierarchies*

Landscape structure is one important element of a broader range of determinants in plant protection. There are different levels of hierarchy in a landscape, in the same way as there are levels of biological organization (De Wit, 1993), of social organization (Allen and Starr, 1982) – where decisions are made (not to act being also a decision) – and of social fabrics. All these levels are of critical importance in the functioning of plant–pest systems, and of their management (or mis-management). This is further illustrated below.

2.7. *Policies and decisions*

This aspect is illustrated in the case of insect pest management. Many insecticide sprays that rice farmers apply in Asia are unnecessary, targeting leaf feeding insects in the early crop stages (Heong and Escalada, 1997). Such leaf damages have no yield consequences (e.g., Graf et al., 1992). Instead, the early season sprays damage the ecosystem services (e.g., insect predators and parasites), thus making the rice crops vulnerable to invading pests such as the planthoppers and late season leaf folders (Heong and Schoenly, 1998). Despite these negative effects, insecticide use tends to increase because farmers are often “locked” into continuing such unsustainable practices (Tisdell, 2000). Some of the factors leading towards this are ignorance, lack of information about side effects, aggressive advertising and marketing by pesticide companies and loss aversion attitudes of farmers. Using a psychometric model, Escalada et al. (2006) showed that in Laos farmers' spray decisions were strongly influenced by subjective norm attitudes or peer pressure, the village heads and government officials being the most influential referent groups. In the Philippines extension technicians were also found to play significant roles in onion farmers' pesticide misuse (Tjornhorm et al., 1997). In China, where government officials promoted a pesticide first policy and subsidize costs, pesticide overuse was the direct consequence (Widawsky et al., 1998).

3. Selected examples of rice-pest systems

This section makes use of the framework of Fig. 1 as a tool to explore a few rice-pest systems. The pictogram of Fig. 1 will thus be adapted below to special cases. These diagrams are therefore meant to guide the reader to explore the functioning of the rice-pest systems, each one in turn; they should not be seen as blanket recommendations we wish to put forward to the reader. In the following set of rice-pest systems, the black arrows indicate relationships that have major implications on the functioning of the crop-pest system and/or for its management. Grey arrows represent relationships that may be less important; a grey arrow, however, does not imply that the corresponding association is unimportant or should be ignored.

3.1. *Planthoppers*

Since the beginning of the green revolution, a range of closely-related Delphacid planthoppers have caused considerable problems for rice farmers in Asia. These include the brown planthopper (*Nilaparvata lugens*), the white-backed planthopper (*Sogatella furcifera*) and the small brown planthopper (*Laodelphax striatellus*). All these species were maintained at low levels in tropical rice paddies prior to the advent of high-input farming – presumably by natural enemies, only causing damage in northern Asia (China, Korea and Japan) when blown northwards by converging winds (Shepard et al., 1991; Otuka et al., 2009). The association between the emerging pest status of planthoppers and agricultural intensification in the 1960s and 70s pointed to the effects of contemporary farm management practices in promoting build-up of hopper populations and ultimate losses in tropical rice (Shepard et al., 1991). Experimental and field evidence has since drawn attention to the role of insecticides in reducing the efficiency of natural enemies and inducing resurgence outbreaks of planthoppers (Wilby et al., 2005); meanwhile, the excessive use of chemical fertilizers and the short times between successive rice crops promoted hopper fitness and stimulated oviposition (Lu et al., 2004). Taken together, this evidence offered clear mechanistic links between farmers' practices vis-à-vis nutrient (Lu et al., 2004, 2006) and insecticide inputs, and the outbreak of planthoppers causing hopperburn and eventual yield reduction. This has led some observers to suggest that planthopper populations and outbreaks are ‘sensitive barometers of [crop] mismanagement’ (Sogawa et al., 2009).

As indicated in the pest management tetrahedron (Fig. 2), and based on the evidence presented above, planthoppers as pests are directly linked to the human summit because humans ultimately cause planthopper outbreaks. Indirect links between H and P, through C and E depict mechanistic links related to i) higher crop vulnerability that results from high nutrient inputs and successive crops, and ii) weak environmental resistance resulting from insecticide-induced depletion of natural enemies. Based on this conceptual framework, improved management of planthoppers must then focus on human-influenced pest population events. This suggests that plant protection systems may need reform to encourage sustainable practices instead of pesticides, so that farmer training programs can effectively avoid unnecessary insecticide use. Farmers may require training to avoid excessive insecticide use and comprehend the regulatory ecosystem functions provided by natural enemies. Reductions in planthopper incidence coincided with the removal of pesticide subsidies in Indonesia in the 1980s (Conway and Barbie, 1988). The implementation of large-scale IPM field schools and non-formal education campaigns in the 1990s (Huan et al., 1999, 2008; Heong et al. 2008) show that strategies that targeted the human summit H to achieve improved pest management met with apparent success.

Meanwhile, whereas alternative strategies showed some promise (i.e., HPR), they have proved unsustainable given the high adaptation potential inherent to high-density populations of such highly genetically flexible insects (Wilby et al., 2006).

3.2. *Rice tungro*

The rice tungro disease (RTD) pathosystem involves two virus species, one major vector, and the rice crop (Azzam and Chancellor, 2002). Compared to other pathosystems, the RTD pathosystem thus appears much more complex, because of the larger number of biological components it involves.

Synchronous crop establishment has long been considered one element for RTD management (Loevinsohn, 1984; Cabunagan et al., 2001), because synchronous crop establishment, and therefore, non-rice periods break the “Green Bridge” (Zadoks and Schein, 1979) between rice crops. There are four main reasons to bring the green bridge strategy to bear. First, the main vector of both viruses, the green leafhopper (*Nephotettix virescens*) is monophagous, specialized in feeding on cultivated rice and a few related species only. Second, the vector does not usually disperse over large distances: the half-distance for dispersal is about 1 km (Savary and Willocquet, unpublished), with a maximal range of 30 km (Azzam and Chancellor, 2002). Third, a fallow period breaks the polyetic process of transfer of inoculum from an infected to a healthy crop stand. The efficiency of synchronous versus asynchronous crop establishment in controlling RTD has been strongly supported by simulation studies (Holt et al., 1997) and demonstrated in actual farmers' field work (Chancellor et al., 2006). Lastly, the viruses are semi-persistently transmitted (Azzam and Chancellor, 2002), enabling the above three factors to play a full role.

The physical climate can have important consequences on RTD epidemics, especially where the disease is not endemic: the rainy season favours rapid vector population build-up, as well as it enhances early emigration of vectors from field to field, thus favouring disease transmission (Chancellor et al., 1996; Cooter et al., 2000; Azzam and Chancellor, 2002). Yet, the population size of the vector is a poorer predictor of disease risk than is the size of the viruliferous fraction of the total vector population (Savary et al., 1993). Preventive insecticide applications, once recommended for RTD control, are therefore poorly grounded.

Several options for RTD management have been explored. Insecticide use, an option extensively used in the past, does not appear reliable, efficient, or cost effective (Azzam and Chancellor, 2002), in addition to the collateral risks and secondary costs it entails. Roguing diseased rice plants is effective only at low disease intensity, and is required to be frequent and precise, rendering it difficult to implement. On the other hand, interestingly, direct-seeded crops appear to be less conducive to RTD than transplanted ones (Azzam and Chancellor, 2002).

An important option for RTD management is also HPR, as concluded by Azzam and Chancellor in their 2002 review. Two types of resistance can be considered: resistance to the main vector, and to the viruses. The former has been extensively addressed, but has the classic drawback of (insect) populations adapting to resistances (Dahal et al., 1990). The latter is under active investigation (Lee et al., 2010; I.R. Choi, Pers. Comm.). Progress may also derive from a combination of both types of resistances (Shibata et al., 2007).

While progress is being made in developing varieties with resistance to Tungro viruses (especially RTSV, I.R. Choi, Pers. Comm.), the overall management of the pathosystem is portrayed in Fig. 3, with a strong element related to C (crop synchrony and the available resistances), P (removal of inoculum sources, including, e.g., infected volunteer plants and presence of neighbouring infected fields), and their necessary connections with H (human decisions towards crop synchronization and variety use). In this simplified diagram, we accept the underlying hypotheses associated with downplaying (shaded arrows) the role of the environment, whether physical (which is given where the disease is endemic) or chemical (including insecticide use).

3.3. *Rice leaf blast*

The underlying epidemiological principles for rice blast management were reviewed by Teng (1994b), who distinguished four types of management tools: knowledge, physical,

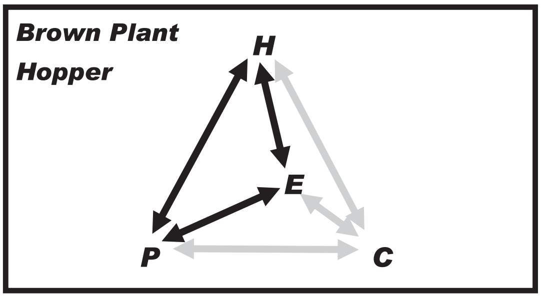

Fig. 2. The brown planthopper pest system. H: negative effects of pesticide ab- and misuse. E: importance of natural enemies of the BPH. C: general and specific resistances; habitat (natural enemies), crop microclimate. P: very large range of insect migrations.

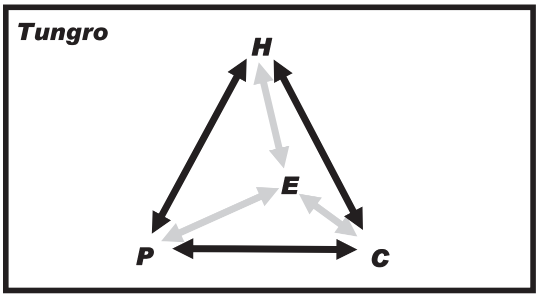

Fig. 3. The rice tungro pathosystem. H: Synchrony of crop establishment (collective decision). E: (environmental effects on vector populations). C: Host plant resistance to (1) the vector (partial), and (2) the viruses. P: reduce the inoculum sources of the two viruses (ratoons, synchrony).

communication, and policy, each of them having effects on initial inoculum (x_0) and/or the apparent rate of epidemics (r). The knowledge tools primarily refer to Humans in the tetrahedron; they include systems analysis and problem definition techniques, forecasting and decision aids or support systems, and cultural knowledge. They also refer to the use of fungicides, one important management tool in many rice-growing countries. Physical tools, as defined by Teng (1994b), incorporate seeds with HPR to blast (Crop), as well as components that change the environment (Environment) to which blast epidemics are so sensitive (Teng et al., 1991). The communication tools also refer to Humans, with the array of multimedia communication and learning technologies, from low- to high-tech, as well as farm demonstrations. The policy tool also refers to Humans; it includes regulations concerning fungicide and chemical inputs, varietal release and deployment policies and regulations, and quarantine and seed health principles and regulations.

The information synthesized by Teng et al. (1991) and Teng (1994b) for blast management leads to the structure shown in Fig. 4. Only key examples of how this structure operates can be given here. Host plant resistance is central to blast management (Zeigler et al., 1994). Variability of the pathogen (see, e.g., Zeigler et al., 1994; Leong et al., 1994; Leung et al., 2002) also is one key element for management, since it directly affects the efficiency of HPR. Yet again, fungicide use often represents one important element of disease control; efficiency and relevance of its use strongly depends on the meso- and micro-climatic environment, as well as on the varieties (Teng, 1994b).

Thus, Fig. 4 involves all summits of the Pest Tetrahedron, with a strong contribution of H on E (which includes, e.g., the chemical environment, altered by fungicide applications) and on C (the crop and plant physiology); of P, with the diversity of the pathogen, and the influence of E (including the microclimate) and C (including, especially, HPR).

3.4. Sheath blight

Rice sheath blight, caused by *Rhizoctonia solani* AGI-1A, is particularly important in intensive rice production systems, especially affecting crops with high attainable yields. Average yield losses of 5–10% have been estimated for tropical lowland rice in Asia (Savary et al., 2000b), which makes sheath blight the most important disease in tropical Asia as a region. The pathogen has a very wide host range, including many weed species occurring within the fields, or on nearby levees (Ou, 1985). No source of complete resistance has been identified for this disease, and the likelihood of such resistance is low, given the low level of specialisation of the pathogen. Partial resistance may however provide an avenue to reduce epidemics (Pinson et al., 2005; Srinivasachary et al., 2011).

The fungus does not produce spores, and lesion multiplication occurs through runner hyphae produced from lesions, spreading on tissues, and differentiating infection structures to establish new lesions (Ou, 1985; Mew, 1991). Disease spread between tissues belonging to different tillers, plants, or hills thus requires contact between tissues. Canopy wetness and frequency of contact between host tissues are two key factors favouring disease epidemics (Savary et al., 1995).

Manipulation of the crop canopy to decrease contact frequency and canopy wetness can thus provide a means to reduce sheath blight epidemics. One entry point corresponds to the crop establishment method. Sheath blight intensity has been shown to be strongly reduced in randomly direct-seeded crops at reasonable seeding rates, compared to crops established from transplanted seedlings (Willocquet et al., 2000). The latter type of canopy structure generates strong local aggregation of host tissues, which favours within-hill disease intensification, enabling disease extensification at canopy closure. When available and affordable, efficient fungicides can also provide a good protection to disease development (Groth and Bond, 2007).

Within the tetrahedron framework (Fig. 5), cropping practices (including crop establishment method, crop density, fertilizer inputs, and fungicides) are currently the main options to manage sheath blight. Improvement of the level of partial resistance in rice varieties, which will incorporate traits for partial physiological resistance and/or disease escape through morphological characteristics (Willocquet et al., 2011), will further improve disease management (Srinivasachary et al., 2011).

4. Perspectives and concluding remarks

4.1. Validity of the above framework for future research and applications

The tetrahedron framework used in this review suitably accounts for the functioning of a range of rice-pest systems. It also suitably incorporates the principles and goals we outlined above. Important questions are (1) whether this framework and the principles attached to it will be valid in the future, and (2) steps to consider for the practical use of this structure.

As global economic, social, and climatic changes take place, agriculture necessarily evolves, and so do rice pests. It would seem that some rice pests are actually likely to become less frequent, and thus have lesser impact on rice-based agrosystems, while others may become far more important than they used to be (Savary et al., 2005; Reddy et al., 2011). The term 'important' needs qualification, and refers to crop losses due to pests, both qualitative and quantitative

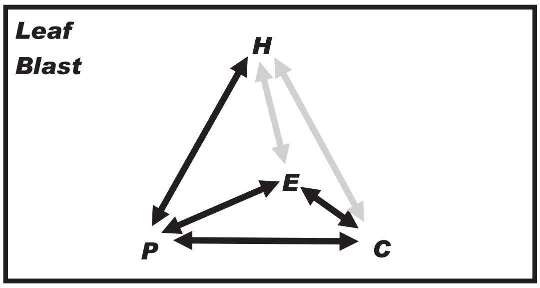

Fig. 4. The blast pathosystem. H: fungicide use, crop synchrony, host diversity (between and within fields). E: importance of (physical) conditions for infection, sporulation. C: Host plant resistance P: Diversity of the pathogen, and very strong potential for adaptation.

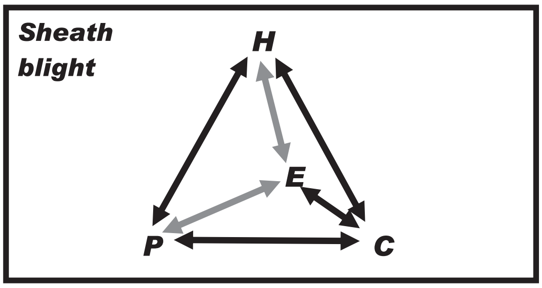

Fig. 5. The sheath blight pathosystem. H: Crop establishment method, fertilizer (especially N) input, fungicides. E: Rainfall, fungicide half-life on/in canopy. C: Crop density (fertilizer use), crop establishment method, microclimate (canopy wetness duration).

(Savary et al., 2006). Of concern are the major yield-reducers, as well as organisms that may cause a reduction in crop value, including nutritional, e.g., through the production of toxins by pests.

4.2. *Emerging pests and diseases*

Because of changes in agricultural systems and shifts in crop health (Savary et al., 2011), the above framework therefore needs to be adaptable, supported by field evidence, and regularly up-dated. Relevant field data (e.g., Savary et al., 2000a) will help determining priority targets for pest management and, identifying potentially harmful organism that may become actually emerging threats. As this review shows, this applies to a wide range of organisms, including fungi such as *Ustilaginoidea virens*, the cause of false smut, which causes crop (quality) losses at low levels of (panicle) infection, as well as pests which can be responsible of very severe yield losses when population densities are high, such as the planthoppers.

The white-backed planthopper has been a concern in rice for decades; however, it previously took second place to the more prolific and more problematic brown planthopper (e.g., Shepard et al., 1991). Recently, however, the white-backed planthopper has emerged as the principal species in planthopper assemblages in India and particularly in East Asia (Sogawa et al., 2009). Associated with this recent community shift, the Southern Rice Black Streak Dwarf virus (SRBSDV) has rapidly spread in China and northern Vietnam (Zhang et al., 2008; Zhou et al., 2008; Zhou, personal communication). There are strong indications that such overall community and specific pest status shifts are related to widespread changes in cropping practices and shifts in varieties deployed. This points at the human factor as a direct or indirect cause of emerging crop health problems in rice. The shift in the status of the white-backed planthopper has been linked to the rapid and widespread adoption of hybrid rice varieties, especially in East Asia (Sogawa et al., 2009). Whereas a direct mechanistic link between hybrid rice and hopper abundance or fitness has not yet been demonstrated, evidence suggests that management practices unique to, or predominantly associated with, hybrid rice and not associated with inbred varieties have produced the recent shifts (Cheng, 2009; Horgan, unpublished data). These practices could be sociologically- or market-driven through links between chemical suppliers and seed companies (Heong, unpublished), since, as indicated above, planthoppers respond predictably to improper insecticide use. However, the narrow genetic basis of hybrid varieties (which require rare CMS parental lines; Sogawa et al., 2009), suggests that white-backed planthoppers might be specifically favoured by the predominant rice hybrids over other planthopper species. The narrow genetic basis of rice hybrids links directly to the crop summit (C) and, when relevant field data become available in the future, might indicate that modern hybrid varieties require substantial broadening of their genetic diversity.

Emerging diseases include *Fusarium* spp. associated with new disease complexes (Huang et al., 2011a, 2011b), which seem associated with new morphological characteristics of rice panicles in both inbred and hybrid material. One concern is that some of the causal fungi are known to produce toxins, possibly rendering the harvest unsuitable for human consumption. Another emerging disease is false smut (*U. virens*), which distribution has been characterized from the agricultural, environmental, and geographical point of view in India (Reddy et al., 2011). One result of this latter study points at a significant positive statistical linkage between false smut intensity at the district level, and the extent of hybrid rice use. In itself, such a statistical association only provides circumstantial evidence, and no scientific proof. It does however point at a knowledge gap and the need for research investment.

4.3. *Multiple pests and disease systems*

Ultimately, sustainable pest management and the science that provides its foundation will remain relevant only if it serves the purpose of sustaining sufficient ecosystems services, including food for the poor, in a changing world. One may then consider rice health as a whole, where all four summits of Fig. 1 would be involved. Depending on the production situation and on the objectives of agricultural production, there will be associated, unavoidable pest problems, which can be seen as a series of niches in a multiple pest profile (McRoberts et al., 2003). Much anticipatory research is needed at the whole system level to predict across a hierarchy of questions (Savary et al., 2011) – What will these new profiles be? How harmful can they be? What sustainable management options should be considered? Research, however, while necessary, is not sufficient (Jeger, 2000). It needs linkage with organizations, structures, policies and governance.

4.4. *Organizations, structures, policies and governance*

Another set of hierarchy levels is materialized by the levels where decisions are made (not to act being also a decision; Zadoks, 1981): from (1) the individual farmer, to (2) farmers communities (3) farmers, inputs providers, and markets, to (4) provincial, and (5) governmental levels.

Pest management structures were established in many developing countries in the 1960s and 1970s and have not significantly changed in their organization. The 'agrochemical era' (Rossiter, 1975) promoted prophylactic use of pesticides (especially insecticides), which were incorporated into the Green Revolution packages. Despite some minor changes in some countries, the same organizational structures, policies and governance mechanisms are still in charge today of IPM research, development, and implementation.

The Green Revolution saw organizations established aimed to deliver material inputs, such as seed, fertilizers and pesticides, in order to ensure agricultural outputs. Today, IPM is not based on inputs, but on knowledge, where farmers learn about the rice agroecosystem and make decisions, especially about insecticide use, variety deployment, crop establishment, and crop management (Matteson, 2000). The traditional structures that govern pest management thus seem ill-equipped to lead IPM research and extension, and in some cases may become road blocks to successful IPM. Officials in these traditional organizations adopt procedural and political rationality in their decision-making, and thus are unable to facilitate reforms in practices. These organizations, their policies, structure and governance will need to be radically re-engineered to ensure the safe-guarding of natural resources and the use of public goods, instead of factor inputs only.

In many developing (and developed) countries, chemical retailers or employees of chemical companies play a critical role as source of advice to farmers. This is equivalent to what would happen in public human health if chemical companies or chemists were directly advising patients on medicines to take without physicians' advice. Plant protection systems based on "crop health clinics" (Danielsen and Kelly, 2010), or "plant health doctors", independent from the chemical private sector, would benefit farmers and society, and could reduce pesticide abuse (Bentley et al., 2009). As in public health, too, crop insurance systems could provide a mechanism to protect farmers from losses due to pests, and to reduce pesticide use (Rola and Sanchez, 1992; Feinerman et al., 1992; Chander, 2005). A supporting advice and insurance organizational system, run by cooperatives or private companies independent from the private agrochemical sector, may provide a relevant way to (1) deliver advice services based on IPM principles, and (2) insure farmers in case of losses, on the basis of predictions of the intensities of yield-reducing factors. These would correspond to prevention and mitigation of risks associated with crop losses caused by diseases and insects (Salimonu and Falusi, 2009), and provide a strong incentive for farmers to use IPM principles. Such a system would be knowledge-intensive, and would require strong policy support for its development. Both components, plant health clinic and crop insurance, have been advocated and used in the past decades, but with limited expansion. Bayesian analytical frameworks have been recently introduced in crop protection (Yuen et al., 1996; Hughes et al., 1999; Madden, 2006), which may now help progress. These can be used to implement supporting systems for pest management (e.g., Hughes and Madden, 2003; Esker et al., 2006). The use of decision theory and Bayesian approaches could be very useful to implement such a risk-management framework with respect to decision making tools, estimation of predictors of crop health problems, and insurance cost estimation (Bekkerman et al., 2008). Such a framework may have strong impact in the implementation of sustainable pest management strategies at different scales, from farmers, to consumers, and societies.

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