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Applying ecological engineering for sustainable and resilient rice production systems

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Abstract

Global changes will affect rice ecosystems at local levels. Although issues of climate change have received most attention, other global changes will have more immediate impacts on crop productivity and health. These changes include the phenomenal advances in modern industrial output, especially in China and India, in mechanization, in communications technology and advertizing, in transportation networks and connectivity, as well as demographic shifts toward urban centers. Driven by policies around food security, market impacts on crop production, and trade regulations, these changes will define crop production systems into the future, impacting rice biodiversity and ecosystem function and giving rise to new pest and disease scenarios. This paper presents a framework for a holistic approach to 'rice ecosystem health' aimed at securing food production while protecting farmer, consumer and ecosystem health. Recent advances in environmentally friendly agriculture, including ecological engineering, are central to the sustainability and resilience of rice ecosystems; but require support from policy to ensure their best effects. This paper introduces some recent advances in the methods of ecological engineering based on research conducted in the Philippines.

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Keywords: Agroecology, climate change; flower strips, global changes, planthoppers, vegetable strips;

1. Introduction

1.1. Rice production in a changing World

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Rice is the principal staple food for more than a third of the world's population. Over 90% of the world's rice is produced and consumed in Asia and between 40 and 46% of all irrigated cropland in Asia dedicated to rice production[1,2]. As the World's human population continues to grow and the availability of agricultural lands decline, estimates are that the World must produce an additional 115 million tons of rice by 2035 to meet increasing global demands[3]. Whether these estimates are correct or not, they have been responsible for driving science and policy around rice production since the beginning of the new millennium, particularly in Asia. This has led to calls for greater investment in science and technology for rice agriculture, an emphasis on intensifying rice production and on strengthening partnerships engaged in rice production, rice provisioning, and marketing[4,5].

Emerging agricultural policy in the 21st century will be implemented amidst a backdrop of rapid global changes in society and the environment: changes in society include changes in the ways in which humans use resources, in human productivity and in social connectedness[6]; environmental changes include climatic anomalies such as increasing global temperatures and the frequency of extreme weather events, as well as declining biodiversity and eroding ecosystem functions[7]. As these factors continue to change, they will impact the nature of rice production from global to local (farm) scales. Furthermore, given the instability of the global economy, particularly since 2008 (when the World experienced global food and economic crises at the same time), demands for increased food production have been met with calls for greater involvement of the private sector in developing strategies and guiding science[5]. As a result, the current production scenario for many rice farmers consists of demands to increase productivity with increasing pressure through advertising and efficient marketing to intensify inputs. In many regions, this has contributed to tremendous changes in rice landscapes, particularly in lowland irrigated rice systems, and often drives farmers toward questionable intensification methods[8,9]. Without proper regulation of farming practice and especially regulation in the nature and use of farm inputs such as pesticides, intensification could lead to global food insecurity by reducing the efficiency of key rice ecosystem functions.

1.2. Increasing insecticide use and its consequences

Trends in the imports of agricultural inputs to rice producing countries show a sustained increase in the availability and use of agrochemicals, including fertilizers and pesticides, over the last 50 years. However, between 1995 and 2002, China and India both shifted from being net pesticide importers to major exporters, as both countries invested in their chemical industries[10]. At the same time, pesticide imports into several Asian countries including Bangladesh, Thailand, Indonesia and Vietnam began to grow exponentially (Fig. 1.)[10]. Chemical insecticides made up much of these imports. With such a high availability of insecticides, new tools in social connectivity and advances in marketing strategies have been used to efficiently deliver the insecticides to farmers and encourage them to increase their applications[11]. One common strategy has been to create demands for pesticides by developing prophylactic application schedules which are distributed to retailers or directly to the farmers. The sudden increase in insecticide use by rice farmers from the beginning of the 2000s, is thought to underlie the simultaneous occurrence of pest outbreaks, including planthoppers (Homoptera: Delphacidae) and leaffolders (Lepidoptera: Pyralidae), at several sites throughout Asia[12,13]. For example, it is estimated that since 2000 China has lost about 1 million tons of rice production annually because of planthopper damage; over 3 million hectares of rice was damaged in Thailand between 2009 and 2011[14]; and an estimated 200,000 hectares of rice was destroyed in Central Java (Indonesia) in 2011 alone (Horgan and Stuart, unpublished data). The outbreaks of planthoppers in particular were so bad, that many regions experienced 'hopper storms' at the time of rice harvest, as displaced planthoppers were attracted to city lights becoming a public nuisance and affecting economic activities including restaurants, cafes and retailers (personal communications with farmers in Indonesia and China).

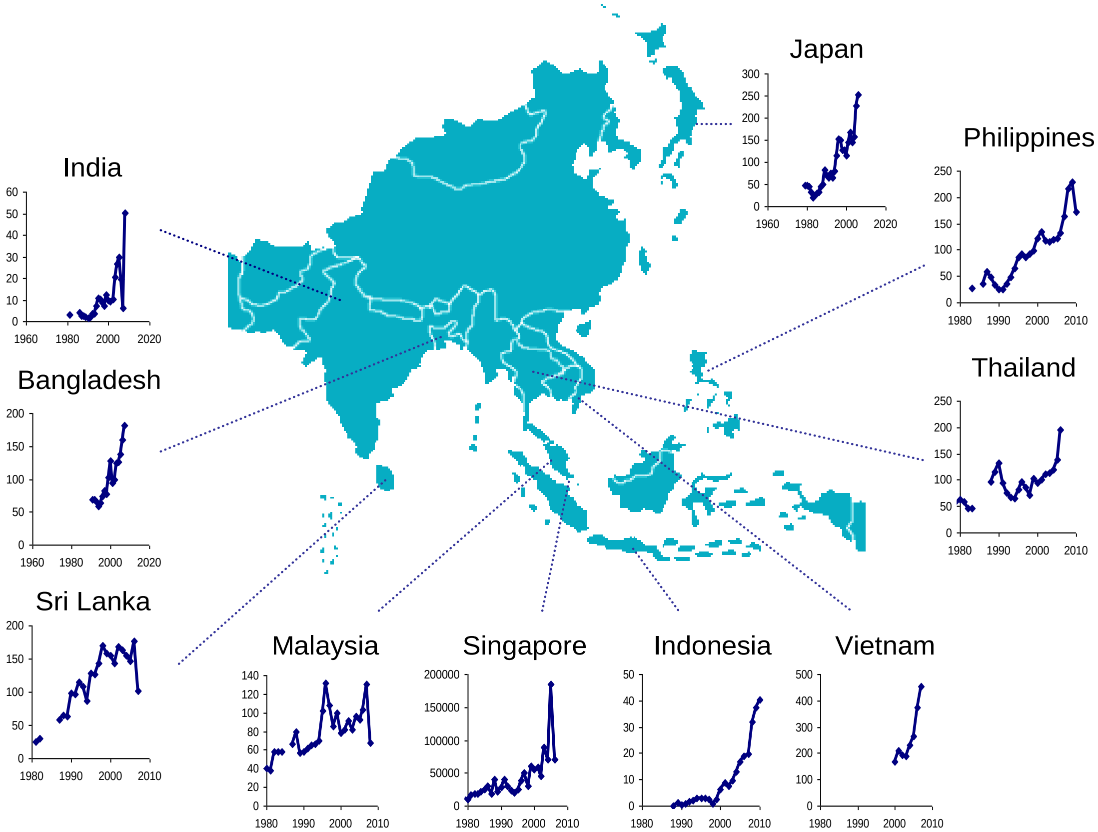

Fig. 1. The value of insecticide imports into 10 Asian countries (US\$1000/Km^2 of land area) between 1960 and 2010 (data from FAO 2015).

Clearly the prophylactic use of insecticides has created some imbalance in rice ecosystems. For several years now, researchers have attributed insect outbreaks in rice fields, particularly the outbreaks of planthoppers, to the overuse of chemical insecticides[15]. This occurs in two ways. The first can be referred to as physiological resurgence. Physiological resurgence is the result of hormoligosis, that is a physiological response by the target insect to chemical toxicity that results in increasing fitness. The mechanisms underlying hormoligosis have not been elucidated; however, in planthoppers and other insects the ultimate responses have included higher fecundity, increased male and female fertility, increased feeding, and a greater dispersal capacity[16,17,18,19]. These factors result in higher planthopper densities and increased damage to rice. The second mechanism can be referred to as ecological resurgence. Here, the insecticides reduce the diversity, abundance or efficiency of the natural enemy component of the rice ecosystem. The negative effects of insecticides on the natural enemies of important pests such as planthoppers and stemborers (Lepidoptera: Pyralidae) have been well documented[15,20]. Indeed several field studies have indicated how insecticide-treated fields have either lower yields than unsprayed fields or have similar yields to untreated fields thereby representing a net negative effect on farm profitability[21]. Whereas certain chemicals known to cause physiological resurgence have been banned or are currently restricted for use in rice[21], most chemicals will still have potential to cause ecological resurgence. Clearly a new strategy around pest management is required.

1.3. The need for a new emphasis on rice ecosystem health

Several decades of agricultural intensification and insecticide overuse has resulted in a depletion of natural enemy populations, as well as the development of pest populations that are increasingly resistant to insecticides and more virulent against rice varieties[15,22,23]. Furthermore, agricultural lands at a global scale have become depleted of functionally important species such as pollinators[24] and predatory amphibians[25]. Rice fields, particularly in the tropics, have a higher diversity of natural enemies than herbivores, resulting in complex food webs[26]. High complexity in food web interactions is predicted to increase the stability and resilience of rice ecosystems[27]. Conversely, biodiversity loss, and the loss of services provided by the natural fauna of rice fields, is predicted to reduce ecosystem stability and resilience; this will lead to less efficient responses to perturbations such as the insecticide-related physiological resurgence of pests, or climatic-driven increases in pest densities.

Scientists are currently faced with the challenges of increasing food security (including food production, food production, food quality and food safety) while at the same time dealing with climatic uncertainly that requires resilient ecosystems, and a need to conserve or restore biodiversity and optimize ecosystem functions. Ecologically-based pest management methods are one way to achieve these goals while at the same time restoring the ecology of rice landscapes. To achieve efficient rice ecosystems, researchers will need to focus on 'rice ecosystem health' where pesticides are regarded as environmental contaminants that should be avoided as much as possible. Furthermore, natural pest regulation should be optimized and food-webs protected and enhanced by creating conditions that promote biodiversity and the complexity of interspecific interactions. One approach to achieving this is ecological engineering[28].

2. Ecological engineering for rice ecosystem health

Ecological engineering is the deliberate manipulation of habitat for the benefit of society and the natural environment[28,29]. The method is strongly knowledge-based and requires a thorough understanding of the potential positive and negative effects of any interventions by the practitioner prior to implementation. Ecological engineering for pest management mainly focuses on increasing the abundance, diversity and function of natural enemies in agricultural habitats by providing refuges and alternate or supplementary food resources[28,30]. Ecological engineering is a component of agroecology that stresses precision (a feature of engineering) in the outcome of some intervention. Whereas the concept has been applied with some certainty of effect in ecosystem restoration and landscape productivity, using plants of function that often act as biofilters or to supply nutrients to the system[31]; the concept is still in its infancy as regards pest management, particularly in rice. However, there are examples from other crop production systems where the method has been successfully applied to pest management. For example, the planting of buckweed, *Fagopyrum esculentum* Moench, as a cover crop in vineyards[32] and Alyssum, *Lobularia maritima* (L) Desv., between rows of vegetables[33] provide resources for predators and parasitoids resulting in reduced herbivore damage.

2.1. Experience with ecological engineering in the Philippines

As part of a government-funded research program in the Philippines (Department of Agriculture, Bureau of Agricultural Research) and with links and support from the LEGATO (Land-use intensity and Ecological Engineering – Assessment Tools for risks and Opportunities in irrigated rice based production systems) project[34], we conducted a series of experiments in ecological engineering for pest management in rice farms between 2011 and early 2015. During the course of these experiments, and building on our experience, we tested and improved a series of farm designs aimed at increasing the diversity of arthropod natural enemies in irrigated rice fields in the Philippines. Without published guidelines for increasing arthropod diversity, our initial experiments were largely trial-and-error attempts at increasing floral diversity while monitoring insect diversity, rice health and final rice and associated crop yields. Results from these experiments will be presented in future publications and will focus on the effects of habitat manipulations on arthropods (including pollinators), rodents and birds. Here we present our designs highlighting some of the advantages and disadvantages of each and focusing on their potential benefits to food security for small-holder farmsteads.

2.2.1. Floral and vegetation strips

Early literature on ecological engineering for rice pest management largely focused on integrating flower or vegetable strips into rice landscapes[9,30]. Because rice is periodically flooded, rice fields are normally surrounded by raised earthen levees known as 'bunds'. Rice bunds were recognized as a convenient location for planting strips of 'upland' vegetation that would not compete with the semi-aquatic rice plants. Rice bunds normally function to direct and maintain water in the rice paddies, but are also used by farmers as walkways between rice fields. Farmers manage their bunds in several different ways, including maintaining the bunds free of weeds and generally bare, encouraging grasses or weeds on the bunds as forage for animals or growing some crop along the bund to optimize farm space and supplement farm income[35]. Such crops may include grasses as animal forage (i.e., common in Bali, Indonesia: personal observation) or hardy crops such as beans and taro (i.e., common in the Philippines and Indonesia[35]). Whereas growing crops on rice bunds is common, farmers generally do not see these as functionally significant to pest management – indeed many farmers will spray the bund crops.

Before initiating our experiments we conducted interviews with stakeholders including officers of the Department of Agriculture (Philippines) and rice farmers. Based on focus group discussions we determined the following criteria for suitable bund crops to be used in vegetation strips:

- Plants should be grown from seed with no need for transplanting.
- Plants should be fast-growing, able to compete with weeds, and require minimum attention or care.
- Plants should be early-flowering.
- Plants should have fruits or vegetative structures that are of some value to the farmer, either for commercial or personal consumption/use.
- Plants should have good production under minimal husbandry.
- Plants should repel or be otherwise unfavorable for the pest insects of rice.
- Plants should attract beneficial arthropods either as a refuge or a source of nectar or pollen.

In 2011 we planted bunds with ladyfinger (local name: okra; *Abelmoschus esculentus* Moench) and in 2013 with mungbean (local name: mungo; *Vigna radiata* L. Wilzeck) and string bean (local name: sitao; *Phaseolus vulgaris* L.). This was to increase the structural diversity of the rice fields. We expected an increase in structural diversity to increase predator abundance, particularly the abundance of spiders[36]. Our preliminary results indicated that spider abundance did increase, and that the ratio of planthoppers to spiders was lower among rice plants in fields close to planted bunds; however, we also noted that rat damage to rice was often associated with the planted bunds – since the rats used the bunds as sheltered walkways by which they could access the rice tillers. Planting bunds with string beans produced about 3.5Kg of beans per meter of bund and both the mungbeans and stringbeans were noted to provide perches for predatory bunds. Mungbeans in particular were rarely damaged by herbivorous insects.

2.1.2. High diversity vegetation patches (HDVP)

Based on our experiences in 2013 when rat damage seemed to be associated with planted rice bunds, we determined that vegetation strips should be avoided in areas were rodents are likely to be problematic. The relationship between rodent damage and the vegetation on rice bunds has not been clearly determined; however, guidelines for rice bunds suggested that the bunds should be no more that 15cm high to prevent rats from tunneling into them and should be largely bare to avoid providing cover for rats[37]. We therefore designed a system of expanded platforms along rice bunds for the planting of vegetables (Fig. 2.). The platforms would be planted with a diversity of crop plants to increase floral diversity and provide resources for a larger range of natural enemies and pollinators. Platforms were created at 10m intervals along the bunds of rice fields at six locations in the Philippines (3 on Luzon Island, 1 on Panay Island, and 2 on Minadanao Island). The platforms were constructed by piling paddy soil into a mound that was then flattened and formed into a rectangle of between 30 and 50cm tall (depending on the height of the adjacent bund). The platforms were fertilized using a top layer of cowdung, vermicompost or complete fertilizer (depending on the site and on farmer preferences).

Fig. 2. High diversity vegetation patches on a rice farm in Mindanao, Philippines during 2014.

Four vegetable crops were selected as ‘bund crops’ to be planted on the earthen platforms. These were bitter gourd (local name: ampalaya, *Momordica charantia* L.), ladyfinger, mungbean, and string bean. About one month before rice transplanting at each site, seed of ladyfinger and mungbean were sown directly to the platform soil. At the same time, seed of bitter gourd and string bean were sown to PVC trays filled with paddy soil and maintained in a greenhouse. These were later transplanted to the earthen platforms.

All four crops grew well on the bunds and produced fruits that could be harvested. Across the six sites, patches produced an average of about 10kg of bitter gourd, 8Kg of mungbean, 55Kg of ladyfinger and 50Kg of string beans per 40 patches (the typical number of patches for a 1 ha field). The patches attracted large numbers of pollinators and were used as perches and foraging sites for insectivorous birds such as shrikes (*Lanius* spp.) and trillers (*Lalage nigra*). However, we noted that fruit flies (Diptera: Tephritidae), which damaged many of the bitter gourds, may have benefitted from nectar supplied by other plants (particularly the mungbean) in the same patches. Furthermore, farmers and field technicians noted that the diversity of crops on each patch resulted in intercrop competition and made harvesting and monitoring (for agricultural and scientific purposes) difficult.

2.1.3. Diverse vegetation patches (DVP)

In 2015, based on experiences gained in the previous years, we developed a system that we called ‘diverse vegetation patches’ (DVP). The system was similar to HDVPs described above; however, to avoid problems with patches providing resources for certain pests, and to facilitate harvesting and monitoring, we separated the different crop plants, placing a single crop species on each bund.

In 2015 we examined the potential for 13 crops to be used in such patches. These included bitter gourd, mungbean, ladyfinger, string bean, chile pepper (*Capsicum* sp.), cosmos (*Cosmos bipinnatus*), cowpea (*Vigna unguiculata* L.), cucumber (*Cucumis sativus* L.), luffa (local name ‘patola’: *Luffa* sp.), squash (*Cucurbita* sp.), sunflower (*Helianthus annuus* L.), bottle gourd (*Lagenaria siceraria* Standl.) and winged bean (*Psophocarpus tetragonolobus* [L.] de Candolle). These crops were grown at the six sites on replicated patches and were monitored during rice crop development. The system was more convenient that the HDVP system and allowed improved monitoring of natural enemies and pollinators. The bund crops had significant effects on the diversity and abundance of natural enemies and pollinators with cucumber, squash, luffa and bitter gourd attracting large numbers of both pollinators and beneficial parasitoid wasps. The DVP system also had a higher abundance and increased activity of insectivorous birds. Furthermore, many of the crops, including cucumber, mungbean, bottle gourd, string bean, luffa, chile, and ladyfinger produced large numbers of fruits. Furthermore, chile plants were noted as a possible perennial crop that could be used over successive seasons and were notably attractive to several species of bees.

3. Developing sustainable rice ecosystems

Based on the results of our experiments, we suggest that sustainable and resilient rice ecosystems could be developed using ecological engineering approaches that employ either vegetation strips, HDVPs or DVPs. Each of these methods has potential advantages and disadvantages as indicated in Table 1. We have noted through interviews with farmers that these systems are likely to be most appreciated where vegetables are produced on the bunds or patches to supplement farmer income; however, there is a danger that such patches would induce farmers to spray more insecticides if the bund crops were heavily attacked by pests. For example, we noted cowpeas and stringbeans in Mindanao were often heavily damaged by aphids (Homoptera: Aphididae), and ladyfinger at two sites in Luzon was heavily damaged by okra planthoppers (*Abelmoschus esculentus* [L.] Moench.). Bitter gourd at all sites and in every season were heavily damaged by fruit flies.

Table 1. Relative ranking (1 = high, 6 = low) of different ecological engineering methods based on14 evaluation criteria

Criteria	Bare bunds	Weedy strips	Flower strips	Vegetable strips	HDVPs	DVPs
Costs	1.5	1.5	3	4	6	5
Ease of management	2	2	2	4	6	5
Farmer acceptance	1	6	5	2	3.5	3.5
Rice production	3.6	3.6	3.6	3.4	3.4	3.4
Vegtable production	5	5	5	3	2	1
Insect pests in rice	5.5	5.5	4	2	2	2
Insect pests on bunds	2	2	2	6	5	4
Rats/rat damage	1	5	5	5	2.5	2.5
Natural enemies in rice	6	1	5	4	2.5	2.5
Natural enemies on bunds	6	1	5	2	3.5	3.5
Pollinators	6	2	5	4	3	1
Birds	6	4	5	3	1.5	1.5
Nutrition	5	5	5	3	2	1
Risks of pesticide use	2	2	2	6	4.5	4.5

Clearly, the choice of bund crop should be determined based on identified conditions for successful production and avoiding hotspots of known pest or disease incidence. Some biological or cultural control methods could be applied to reduce losses to the crops; however, we believe that the simple avoidance of vulnerable crop species is a more sustainable solution for ecological engineering. For this reason, in many instances, growing flowers such as sunflower or cosmos can be a suitable alternative to fruit crops. Furthermore, to develop efficient ecologically engineered rice production systems, farmers should pay special attention to their choice of rice variety. Varieties with known resistance to key pests such as planthoppers, leafhoppers or stemborers are preferable[8,23].

To our knowledge, the results from only one previous field study of ecological engineering have been published. This study was conducted in China and used vegetation strips of sesame (*Sesamum indicum* [L.]) and vetiver grass (*Vetiveria zizaniodes* [L.]) as resources for parasitoids and trap plants for stemborers, respecticvely[30]. Insecticides were used in the ecologically engineered rice fields; however, the number of insecticide applications was reduced by 75% compared to farmer fields. Despite this, farmers fields and ecologically engineered fields produced similar rice yields but the ecologically engineered fields saved US$150/ha on insecticides and gained US$120/ha from the sesame seed that was produced on the bunds[30]. Similar field studies have been conducted in Thailand, and Vietnam using flower strips. The preliminary results of these studies indicate similar benefits to natural enemy populations[38].

4. Summary

New directions in research are needed to create healthy rice ecosystems. Healthy ecosystems regard pesticides as contaminants that research has identified as potential drivers of pest resurgence. Healthy rice ecosystems avoid harmful chemicals but also increase the functional diversity of the rice landscape to attract beneficial organisms such as pollinators and the arthropod (parasitoids and spiders) and vertebrate (bird) natural enemies of pests. By enhancing biodiversity in rice fields and increasing the interspecific interactions between the component species in the rice ecosystem, agroecology and ecological engineering predicted to increase the sustainability and resilience of the systems against perturbations – including sudden increases in pest densities. Researchers and pest management practitioners should be aware of the huge increases in pesticide production and marketing as well as the social and economic pressures on modern rice farmers, as they direct policy and develop guidelines for sustainable rice production and increased global food security.

References

1- Khush GS. Origin, dispersal, cultivation and variation of rice. Plant Molecular Biology 1997:**35**: 25-34.
2- *Rice Almanac*, Fourth Edition. Los Baños: International Rice Research Institute; 2013.
3- Bouman B. 'Talking rice' at the food security summit. http://irri.org/index.php?option=com_zoo&view=item&layout=item&Itemid=1135 (accessed 30 November 2015)
4-Cassman KG. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. PNAS 1999;**96**: 5952-5959.
5-Godfray HC, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C. Food security: The challenge of feeding 9 billion people. Science 2010;**327**: 812-818.
6-Horrigan B. *Corporate social responsibility in the 21st Century: Debates, models and practices across government, law and business*. USA:Edward Elgar; 2010.
7-Pereira HM, Leadley PW, Proença V, Alkernade R, Scharlemann JPW, Fernandez-Manjarrés JF, Araújo MB, Balvanera P, Biggs R, Cheung WWL, Chini L, Cooper HD, Gilman EL, Guénette S, Hurtt GC, Huntington HP, Mace GM, Oberdorff T, Revenga C, Rodrigues P, Scholes RJ, Sumaila UR, Walpole M. Scenarios for global biodiversity in the 21st century. Science 2010;**330**: 1496-1501.
8-Horgan FG, Crisol E. Hybrid rice and insect herbivores in Asia. Entomologia Experimentalis et Applicata 2013;**148**:1-19
9-Westphal C, Vidal S, Horgan FG, Gurr GM, Escalada M, van Chien H, Tscharntke T, Heong KL, Settle J. Managing multiple ecosystem services with flower strips and participatory approaches in rice production landscapes. Basic and Applied Ecology 2015. Forthcoming.
10-Food and Agriculture Organization of the United Nations. *Statistics division*. http://faostat3.fao.org/home/E (accessed: 15 October 2015).
11-Spangenberg JH, Douguet JM, Settele J, Heong KL. Escaping the lock-in of continuous insecticides spraying in rice: Developing an integrated ecological and socio-political DPSIR analysis. Ecological Modelling 2015;**295**: 188-195.
12-Catindig JLA, Arida GS, Baehaki SE, Bentur JS, Rattanakarn LQW, Sriratanasak W, Xia J, Lu Z. Situation of planthoppers in Asia. In: Heong KL, Hardy B. editors. *Planthoppers: New Threats to the Sustainability of Intensive Rice Production Systems*. Los Baños: International Rice Research Institute 2009. Pp 191-220.
13-Cheng J. Rice planthopper problems and relevant causes in China. In: Heong KL, Hardy B. editors. *Planthoppers: New Threats to the Sustainability of Intensive Rice Production Systems in Asia*. Los Baños : International Rice Research Institute. 2009. Pp. 157-178.
14- International Rice Research Institute. Preventing planthopper outbreaks in rice. http://irri.org/resources/publications/brochures/preventing-planthopper-outbreaks-in-rice (accessed 14 September 2015)
15-Kenmore PE, Cariño FO, Perez CA, Dyck VA, Gutierrez AP. Population regulation of the rice brown planthopper (*Nilaparvat lugens* Stål) within rice fields in the Philippines. Journal of Plant Protection Tropics 1984;**1**: 19-37.
16-Wang A-H, Wu J-C, Shu Y-S, Liu J-L, Yue J-F, Wang M-Y. Selective insecticide-induced stimulation of fecundity and biochemical changes in *Tryporyza incertulas* (Lepidoptera: Pyralidae). Journal of Economic Entomology 2005;**98**: 1144-1149.
17-Yu Y-S, Xue S, Wu J-C, Wang F, Yang G-Q. Changes in levels of juvenile hormone and molting hormone in larvae and adult females of *Chilo suppressalis* (Lepidoptera: Pyralidae) after imidacloprid applications to rice. Journal of Economic Entomology 2007;**100**: 1188-1193.
18-Azzam S, Wang F, Wu J-C, Shen J, Wang L-P, Yang G-Q, Guo Y-R. 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**: 347-358.
19-Azzam S, Yang F, Wu J-C, Geng J, Yang G-Q. Imidacloprid-induced transference effect on some elements in rice plants and the brown planthopper *Nilaparvata lugens* (Hemiptera: Delphacidae). Insect Science 2011;**18**: 289-297.
20-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**: 193-199.
21-Heong KL, Escalada MM, Van Chien H, Delos Reyes JH. Are there productivity gains from insecticide applications in rice production? In: Heong KL, Cheng J, Escalada MM. editors. *Rice planthoppers: Ecology, management, socio economics and policy.* Beijing: Springer Science and Buisness Media. 2015. Pp. 179-189.
22-Matsumura M, Takeuchi H, Satoh M, Sanada-Morimura S, Otuka A, Watanabe T, Van Thanh D. Species-specific insecticide resistance to imidacloprid and fipronil in the rice planthoppers *Nilaparvata lugens* and *Sogetella furcifera* in East and South-east Asia. Pest Management Science 2008;**64**: 115-1121.

23-Horgan FG, Ramal AF, Bentur JS, Kumar R, Bhanu KV, Sarao PS, Iswanto EH, Chien HV, Phyu MH, Bernal CC, Almazan MLP, Alam MZ, Lu Z, Huang SH. Virulence of brown planthopper (*Nilaparvata lugens*) populations from South and South East Asia against resistant rice varieties. Crop Protection 2015;**78**: 222-231.
24-Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. Global pollinator declines: trends, impacts and drivers. Trends in Ecology and Evolution 2010;**25**: 345-353.
25-Collins JP, Crump ML. *Extinction in our times: Global amphibian decline*. Oxford:Oxford University Press. 2009.
26-Cohen JE, Schoenly K, Heong KL, Justo H, Arida G, Barrion AT, Litsinger JA. A food web approach to evaluating the effect of insecticide spraying on insect pests population dynamics in a Philippine irrigated rice ecosystem. Journal of Applied Ecology 1994;*31*: 747-763.
27-Ings TC, Montoya JM, Bascompte J, Blüthgen N, Brown L, Dormann CF, Edwards F, Figueroa D, Jacob U, Jones JI, Lauridsen RB, Ledger ME, Lewis HM, Olesen JM, Van Veen FJF, Warren PH, Woodward G. Review: Ecological networks-beyond food webs. Journal of Animal Ecology 2009;**78**: 253-269.
28-Gurr GM. Prospects for ecological engineering for planthoppers and other arthropod pests in rice. In; Heong KL, Hardy B. editors. *Planthoppers: New threats to the sustainability of intensive rice production systems in Asia.* Los Baños :International Rice Research Institute. 2009. Pp 371-388.
29-Gurr GM, Heong KL, Cheng JA, Catindig J. Ecological engineering strategies to manage insect pests in rice. In: Gurr GM, Wratten SD, Snyder WE, Read DMY. Editors. *Biodiversity and insect pests: Key issues for sustainable management.* Oxford:Wiley Blackwell. 2012. Pp. 214-229.
30-Lv Z, Zhu P, Gurr GM, Zheng X, Chen G, Heong KL. Rice pest management by ecological engineering: a pioneering attempt in China. In: Heong KL, Cheng J, Escalada MM. editors. *Rice planthoppers: Ecology, management, socio economics and policy.* Beijing: Springer Science and Buisness Media. 2015. Pp 161-178.
31-Mitsch WJ, Jørgensen SE. *Ecological engineering and ecosystem restoration*. New Jersey:John Wiley and Sons. 2004.
32-Berndt LA, Wratten SD, Scarratt SL. The influence of floral resource subsidies on parasitism rates of leafrollers (Lepidoptera: Tortricidae) in New Zealand vineyards. Biological Control 2006;**37**: 50-55.
33-Gillespie M, Wratten S, Sedcole R, Colfer R. Manipulating floral resources dispersion for hoverflies (Diptera: Syrphidae) in a California lettuce agro-ecosystem. Biological Control 2011;**59**: 215-220.
34-Settele J, Spangenberg JH, Heong KL, Burkhard B, Bustamante JV, Cabbigat J, Chien HV, Escalada M, Grescho V, Hai LH, Harpke A, Horgan GH, Hotes S, Jahn R, Kühn I, Marquez L, Schädler M, Tekken V, Vetterlein D, Villareal SB, Westphal C, Weimers M. Cultural landscapes and ecosystem services in South-East Asia – the LEGATO-project. Basic and Applied Ecology 2015. Forthcoming.
35-Foronda VR. Agricultural biodiversity conservation toward sustainable rice-based farming systems. Journal of Development in Sustainable Agriculture 2007;**2**: 167-191.
36-Uetz GW. Habitat structure and spider foraging. In: Bell SS, McCoy ED, Mushinsky HR. editors. *Habitat structure: the physical arrangement of objects in space*. Population and Community Ecology Series. Netherlands: Springer. 1991. Pp 325-348.
37-Brown PR, Singleton GR, Sudarmaji. Habitat use and movements of the rice-field rat, Rattus argentiventer, in West Java, Indonesia. Mammalia 2001;**65**: 151-166.
38-LEGATO/CABI. Ricehoppers: Latest information and issues relevant to managing rice planthopper problems. http://ricehoppers.net/ (accessed 30 November 2015)