Biological Control of Lepidopteran Pests in Rice: A Multi-Nation Case Study From Asia

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Abstract

We provide a case study where Integrated Pest Management (IPM) for rice production systems has been introduced to the Greater Mekong Subregion (GMS). Funded by the European Union (EU), this IPM initiative brought together local and international partners to develop an environmentally friendly and economically sustainable rice pest management strategy for southwestern China, Laos, and Myanmar. A key component of the strategy was to establish 12 Trichogramma spp. rearing facilities (TRFs) that mainly targeted rice stem borers. Four TRFs were established in each of the participating countries. The most promising strains of Trichogramma chilonis (Ishii) and T. japonicus (Ashmead) were selected for production in the TRFs based on extensive field surveys as well as laboratory and field release studies. The project also considered the potential for Trichogramma spp. of each strain to withstand the high temperatures expected under a changing climate. Implementation of the IPM strategy resulted in higher rice yields (2–10%), an increase in natural enemy abundance (e.g., twice as many spiders), and a reduction in insecticide applications (1.5 fewer applications). During a capacity-building program, IPM practices with strong cultural and biological control-based components were promoted among ca 50 IPM trainers and ca 6,400 rice farmers. This case study indicates the potential successes of advanced biological control-based IPM systems. We believe that these systems merit wider consideration, including adaptations for other regions and crops.

Key words: stem borer, leaf folder, Trichogramma, biocontrol, Greater Mekong Subregion

Rice is the staple food for about one-half of the world’s population and is thus highly important for global food security (Muthaya et al. 2014, Heinrichs and Muniappan 2017). The Greater Mekong Subregion (GMS) that includes parts of China, Myanmar, Thailand, Cambodia, Vietnam, and Laos is a focal region for rice production. The region has a rich ethnic diversity (Fig. 1A). For example, it is estimated that a total of 260 to 460 different languages are spoken between Cambodia, Laos, Vietnam, and Myanmar. Furthermore, although the ethnic diversity of the region is widely acknowledged, it is also believed to be largely underestimated, as many remote rural and fishing communities with distinct cultures are overlooked in official statistics (Djité 2011, Ha 2011). In southwestern China (Yunnan Province, Guangxi Zhuang Autonomous Region), Laos, and Myanmar, rice is not only the main staple, but rice also provides jobs and income for a substantial proportion of rural communities. Despite significant improvements in rice production in the GMS over the last 15 yr, rice productivity has remained low in some areas, particularly in Laos and Myanmar (i.e., 3.1–4.9 tonnes/ha in irrigated rice, unpublished results). This has been partly due to the impact of pests (Fig. 1B), diseases, and weeds. Rice yields are higher in southwestern China where hybrid rice varieties are widely planted; however, hybrid varieties have been associated with higher agrochemical inputs, and consequently, a greater instability in pest populations (Hong et al. 2008, Horgan and Crisol 2013). Furthermore, the production of pesticides has dramatically increased in India and China in recent decades. This has resulted in a 3.4-fold...
increase in pesticide use in Asia since the early 2000s, with a large proportion of this directed towards rice (Fig. 1C). Higher pesticide use can decrease farm profitability and affects human and environmental health (Horgan 2017a, b). Despite its importance in the Asian diet, rice farming is not very profitable. Therefore, the application by farmers of substantial amounts of often expensive inputs is often unwarranted.

Rice is attacked by a range of insect herbivores (Matteson 2000). In several rice-producing regions, complexes of stem borers are considered a major production constraint (i.e., white stem borer, *Scirpophaga innotata* (Walker, 1863), in Mindanao, Philippines and Indonesia [Litsinger et al. 2006] and yellow stem borer, *Scirpophaga incertulas* (Walker) in China [Lepidoptera: Pyraustidae]; and striped stem borer, *Chilo suppressalis* (Walker) [Lepidoptera: Crambidae] in China [Horgan and Crisol 2013]). The striped stem borer and the yellow stem borer are considered the most damaging species from these complexes. Cheng et al. (2010) suggest that stem borers regularly cause yield losses of about 20% in rice-producing countries. In some parts of the Philippines and Indonesia, white stem borer can cause tremendous losses to productivity (e.g., 70% whiteheads: Horgan, personal observation) and alternatives to insecticide use are urgently required (Litsinger et al. 2006). Of specific concern from the point of view of pest control is the yellow stem borer. Egg masses of this species regularly consist of several layer of eggs, covered by hairs. In the 1950s, Khan and Murthy (1955) had already reported that mass releases of *Trichogramma minutum* Riley (Hymenoptera: Trichogrammatidae) against yellow stem borer on rice in Hyderabad, India, failed to give satisfactory results and evidence has accumulated to suggest that yellow stem borer egg masses are not accepted by *Trichogramma* in general (Tang et al. 2017).

![Fig. 1.](https://academic.oup.com/jipm/article-abstract/11/1/5/5820906)
Therefore, the success of stem borer biological control can depend on which stem borer species dominates in the target region. To date, control measures have predominantly relied on the intensive use of broad-spectrum insecticides, which has led to increased insecticide resistance and frequent outbreaks of secondary pests such as planthoppers and leaf folders (Horgan 2017b, Horgan et al. 2017). A number of insecticides have been used indiscriminately against rice pests in the past. These include monocrotophos, chlorpyriphos, carbofuran, cypermethrin, cartap hydrochloride, fipronil, and phorate 10 G. Most of these broad-spectrum insecticides are highly toxic to rural communities and pesticide applicators (Pingali and Roger 2012), especially since applicators rarely use protective equipment (Fig. 1C).

Farmers also face issues with regard to plant diseases. The most serious diseases include rice blast and, occasionally, rice smuts and rusts (Ou 1972). Weeds also cause problems for rice farmers in the GMS, particularly where the farmers struggle to implement proper water management during the early stages of rice production. While a large number of pests have been documented from the rice crop, there is also a remarkably rich natural enemy complex. For example, Lou et al. (2014) recorded 889 species of predatory natural enemies and 424 parasites of insect pests from rice fields in China. The authors suggested that each key insect pest in rice is affected by between 50 and 60 species of natural enemies. Therefore, by protecting beneficial species from broad-spectrum insecticides, crop managers can reduce and stabilize pest populations (Settle et al. 1996; Horgan et al. 2015, 2017).

Despite considerable efforts towards increasing the environmental sustainability of rice production in recent years (e.g., China: Xu et al. 2017), the GMS is still faced with major problems regarding sustainable rice pest management (Spangenberg et al. 2015, Flor et al. 2019). For example, at the farmer’s level, there is a lack of knowledge of Integrated Pest Management (IPM), including a lack of knowledge about the rational use of pesticides (e.g., farmers often have a poor understanding of the environmental and health problems associated with pesticides: Horgan 2017a). Furthermore, benign pesticides, e.g., those with higher selectivity, including some biopesticides, are unavailable or have limited availability in most GMS countries. Farmers also have limited knowledge on all aspects of biological control, including the sound production and application of biological control agents (Wyckhuys et al. 2019). Although agricultural advisory services are relatively well developed in southwestern China, they are limited in much of the rest of the GMS (e.g., Laos and Myanmar: Fig. 1D); High temperatures, which are already typical for the region and are expected to further increase under global climate change, can also affect the implementation of IPM measures, and in particular, the efficiency of biological control agents (Wu et al. 2016).

Considering the above, future pest control options in the GMS have to tick many boxes: they must present affordable and innovative alternatives to pesticides that are actively marketed in the region (e.g., Spangenberg et al. 2015, Flor et al. 2019); they should be based on simple, low-input, and straight-forward technologies that are sustainable and appropriate for local replication; and finally, they need to be adapted for a changing climate in order to ensure their long-term effectiveness. Strong institutional capacity and governance networks must also be in place to help promote changes in pest management culture and policy that favor IPM and biological control (Matteson 2000, Spangenberg et al. 2015, Flor et al. 2019).

The case study presented here aimed to introduce biological control-based IPM to rice production systems in the GMS (Horgan et al. 2015, Babendreier et al. 2016). A principal objective of the project was to reduce farmers’ pesticide inputs and to provide an alternative tool for controlling key lepidopteran pests. The alternative was to release *Trichogramma* spp. egg parasitoids that have already been effective in managing lepidopteran pests under a variety of cropping systems (Consoli et al. 2010). Many attempts were made during the last 50 yr to establish *Trichogramma* spp., as a biological control agent in rice. Although these have had varying success, overall, they showed promising results, i.e., rice yields increased by approximately 10–30% and the abundance of natural enemies is generally higher in *Trichogramma* spp. release plots compared with untreated controls (e.g., Tripathi et al. 2017, Sharma et al. 2018). Despite the availability of such information in the literature, there is little existing information on any commercially successful cases of *Trichogramma*-based biological control in rice. In this article, we present the research and implementation framework surrounding the application of *Trichogramma*-based biological control among rice farmers in the GMS. We indicate the activities that were conducted in collaboration with key stakeholders, often including local farmers, during the implementation of the project. We also highlight some of the successes and challenges encountered during the project. The article describes one of the largest biological control projects for rice pest management in Asia (encompassing three countries and establishing 12 production facilities), which could be replicated in other rice-producing countries through national research and extension institutes. By reporting this project as a case study, our aim was for future practitioners to adopt and adapt similar implementation programs to meet their local requirements.

**Rice IPM Case Study: Overall Approach**

The Rice IPM project aimed to sustainably increase rice production in southwestern China, Laos, and Myanmar through multi-regional research and capacity building as well as the implementation of biologically-based pest management that is suited to current and predicted climatic conditions (Fig. 2). Early on, egg parasitoids such as *Trichogramma* spp. were identified as an ideal component of such a project because these natural enemies are effective in a range of crop production systems, including rice, and are relatively easy to mass-produce (Consoli et al. 2010). The project was funded by EuropeAid and implemented by the Institute of Plant Protection-Chinese Academy of Agricultural Sciences (IPP-CAAS), as well as CABI Switzerland, with additional national and provincial partners (Plant Protection Station Xingan, Guangxi Province [PPS], Plant Protection and Quarantine Station Dehong, Yunnan Province [PPQS], Plant Protection Center Laos [PPC], Plant Protection Division, Myanmar [PPD]) and with further support from the International Rice Research Institute (IRRI) and the Hengshui Biocontrol Company, China. The partners made up a strong and supportive institutional base for the project in each of the three countries and regionally. In this 5-yr project, research and technology development first focused on China, with subsequent technology transfer and capacity building conducted throughout the target region.

**Participatory Rural Appraisals**

To develop and implement a biologically based pest management strategy, participatory rural appraisals (PRAs) were first conducted in 10 villages in the GMS to gain insights into farmers’ knowledge, attitudes, and practices related to rice production. Each village was visited during 2–3 d. Transects, seasonal calendars, problem trees, and Venn diagrams were developed, and focus group discussions about pest management were held with 20–40 farmers at each village.
The results indicated that throughout the region, farmers have adopted an intensified production system using modern rice varieties, fertilizers, and pesticides. Input use varied considerably among the three countries with Chinese farmers using the highest amount of pesticides and fertilizers. Chinese rice farmers also had considerably higher yields (e.g., 7 tonnes/ha, unpublished); however, the Chinese farmers were not necessarily better-off because intensification apparently brought an associated range of problems, including higher pest pressures and a need for seasonal loans to pay for inputs. Furthermore, input costs were reported by farmers as generally increasing over time, whereas the price of rice was perceived as declining. Farmers, particularly in Laos and Myanmar, were faced with additional challenges, such as poor infrastructure, limited market access, the poor quality of inputs, and unpredictable weather conditions (droughts and floods) (Fig. 1E and F).

In general, farmers had little knowledge of innovative plant protection technologies or IPM. This resulted in inefficient farming practices, including unbalanced use of fertilizers, overuse of pesticides or the application of unsuitable pesticides, and inadequate protection of farmer health and the environment (Fig. 1C). Lacking alternatives, many farmers continued to practice unsatisfactory and inefficient farming methods such as using broad-spectrum insecticides to avoid potential economic losses (i.e., risk aversion). Farmers were generally interested to improve their crop management, but claimed that their access to education, knowledge, and expertise was limited. Agrochemical suppliers were often the sole or main source of advice for crop and pest management. The farmers generally cultivated small areas (i.e., < 2 ha) and, consequently, they believed that their plots may be affected by pesticide drift from neighboring farms. As such, the best recommendations for IPM would be to implement a village approach whereby farmers within a larger community join forces and harmonize pest management systems. Nevertheless, several studies indicate that the reduction of insecticides can have beneficial effects even at small field scales (Horgan et al. 2017). Based on the results from the PRAs as well as further literature reviews and reviews of locally collected statistics on rice production, the project was implemented in the following locations (Fig. 3):

**China**: Mangshi City, Yunnan Province; Xing’an County, and Guangxi Autonomous Region

**Laos**: Vientiane Capitol and Sayabouri Province (districts Sayabouri, Phiang, Xienhone)

**Myanmar**: Yangon, Naypyidaw, Mandalay (Paleik), and Sagaing (Shwebo)

**Field Surveys**

Although a number of *Trichogramma* spp. strains are reared worldwide by different laboratories or mass-production companies. It is generally recommended to conduct surveys and collections in target regions to identify suitable local strains (De Clercq et al. 2011). The two main advantages of local surveys are, firstly, that strains can be obtained that are well adapted to the target host and target environment and secondly, that a reliance on locally selected strains minimizes any potential nontarget effects of *Trichogramma* spp. (De Clercq et al. 2011). To qualify for final selection, the species/strains should also be easily mass-reared. Finally, we considered that the selected species/strains should be effective under the potentially higher temperatures and more intense rainfall predicted by climate change models (IPCC 2014).

Two field collections each were conducted in Yunnan Province, Guangxi Autonomous Region, Myanmar, and Laos during 2011 and 2012 (eight collections in total). Each field collection lasted from 5 to 8 d (Fig. 3). All collections were from irrigated fields without recent insecticide applications and with rice at the tillering or booting stages. The other regions were not included in this project due to insufficient feedback from the farmers and service providers.
In the target area of the Mekong River used in these comprehensive surveys, we recorded a low Trichogramma spp. parasitism rate from 661 leaf folder eggs (0–3%) and yellow stem borer egg masses (0–2%) as well as from eggs on the sentinel egg cards (<1%). Slightly higher parasitism was observed from striped stem borer eggs (0–10%). The Trichogramma spp. samples obtained during the collections were shipped to IPP-CAAS, Beijing, for identification (Liu et al. 2016). A number of previous studies have shown that Trichogramma spp. efficiency in parasitizing eggs was reduced by up to 50% after adults had been exposed to simulated heavy rain (i.e., pupal stages exposed to 37°C for 4–12 h) (Guo et al. 2017). One T. chilonis strain was also tested for any potential effects of heavy rain on survival and parasitism rates. No negative effects were observed on adult emergence across three simulated rain intensities (i.e., 19–75 mm precipitation per day) when individuals were exposed inside the host eggs. However, Trichogramma spp. efficiency in parasitizing eggs was reduced by up to 50% after adults had been exposed to simulated heavy rain (Song Kai et al. unpublished data).

Parasitism rates differed among the tested Trichogramma spp. strains in laboratory tests. A T. chilonis strain collected in Cuijia, China, showed significantly higher parasitism of striped stem borer eggs than any other strain (Ko et al. 2014). All strains parasitized more new eggs (<24 h old) compared to older eggs (i.e., 24–48 and 48–72 h). In field tests conducted in China, parasitism of sentinel striped stem borer eggs by Trichogramma spp. released at 50,000, 100,000, or 200,000 wasps per hectare was often low (4–13%) with minor differences between strains and release rates (Ko et al. 2014).
In a field test conducted using yellow stem borer eggs, parasitism by *T. japonicum* (9%) and *T. chilonis* (15%) was similarly low (Tang et al. 2017). Based on the results of these screening studies, the *T. chilonis* strain from Cuijia was selected for mass production in China, whereas locally collected *T. japonicum* strains were selected for production in Laos and Myanmar.

**Trichogramma Mass Production**

To design TRFs, the most effective, low-cost *Trichogramma* spp. production techniques were first determined through consultations with experts and literature reviews and considering the knowledge and facilities available to each of the project partners. The choice of production techniques was also based on results from a range of further laboratory studies on reproduction rates and production times, and on the costs of inputs such as feed, equipment, and labor. The final selected method was based on the rice moth, *C. cephalonica*, as a factitious host, using a rice bran-based diet. Briefly, the method included the following steps. Rice moth larvae were reared in plastic trays that were covered with a mesh screen before adult emergence (Fig. 4A). Adult rice moths were then collected and transferred to rearing cabinets for egg laying (Fig. 4B and C) with the obtained eggs subsequently exposed to *Trichogramma* for parasitization (Fig. 4D). In each country, the production process and management of the production units were designed to accommodate local climatic conditions, the types and availability of rearing materials at each center, and the skill levels of local staff. Quality control measures were adopted in line with internationally accepted standards throughout the whole production chain from rearing the host insects to the final release of *Trichogramma* spp. in the field (Consoli et al. 2010). The main factors checked during quality control each season

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**Fig. 4.** (A) Larval trays filled with rice bran diet, with a mesh lid; (B) A *Trichogramma* oviposition box, to be placed into an oviposition cupboard. (C) Project staff evaluating rearing equipment (oviposition cupboard) at a carpentry workshop. (D) *Trichogramma* parasitizing a host egg. (E) A newly established TRF at the Sayaboury District Plant Protection Centre, Laos. (F) Project meetings (this one in Laos) were regularly held to develop the IPM strategy and to exchange knowledge on rice IPM and *Trichogramma* production.
were parasitism rates, emergence rates, sex ratios, and the incidence of wing deformities among adult *Trichogramma* spp. as well as the hatchability of moth eggs.

Even though TRFs were established with strong links to local plant protection stations (Fig. 4E), production personnel were given further training because the rearing of a biological control agent on such a large scale was a generally new concept for them (Fig. 5A and B). Several training documents were developed during the project, including a detailed 30-min video showing the different steps of host (rice moth) and *Trichogramma* spp. production. Personnel were also trained in quality control procedures and in the economic aspects of production, highlighting the importance of maximizing output per unit cost. Additionally, constantly updated production plans at each TRF helped ensure that *Trichogramma* spp. egg cards were available for distribution to rice fields at the peak of pest occurrence based on the local crop cycles.

By the end of the program in mid-2016, twelve TRFs, four in each country, had been set up. These provided egg cards for farmers’ fields in each local vicinity (Babendreier et al. 2019). Rearing rooms were approximately 100 m² and were mainly established in previously existing buildings, although some were established in newly-constructed, purpose-built buildings (see Fig. 4E for an example of the latter). In China, where rearing activities were first started, biological control agents were delivered for 802 ha in Dehong Prefecture, Yunnan Province, and 818 ha in Xing’an County, Guangxi Province during 2015. One Chinese TRF also supplied *Trichogramma* spp. egg cards to a neighboring county where the incidence of stem borers was high, resulting in a strong demand for sustainable plant protection methods in that county. In Laos, three of the four TRFs became operational in late 2015. In total, 126 ha of rice were treated in 2015 despite the late establishment of the TRFs.

**Fig. 5.** Training activities: (A) Training staff at the pilot TRF in Myanmar. (B) Training TRF staff in Laos. (C) Training of Trainers (TOT) (in classroom) in Laos. (D) TOT in open field in Myanmar (‘insect zoo’ exercise). (E) Farmers training in IPM in Laos (focusing on women). (F) Farmers training in IPM in Myanmar.
Similarly, in Myanmar, production was started late in 2015 with approximately 35 ha of rice treated that year. One further TRF was established at Yeinz Agricultural University, Naypyedaw. This facility had a dual function to educate students about IPM and to provide biological control agents to local farmers. Upscaling of production was observed in early 2016 at some TRFs (Babendreier et al. 2019). As the TRFs became operational, a range of potential challenges to their ultimate success became apparent. These issues included simple methodological errors, e.g., staff leaving host eggs at refrigerator temperatures (4°C) for too long thereby reducing parasitism rates (cf. Bhargavi and Naik 2015). Additionally, invading pests such as rice weevils competed for the moth diet, and in some cases, Habrobracon spp. parasitoids attacked the rice moth larvae directly. These issues were mainly problematic in Laos and Myanmar, where hot and humid climates promoted the development of contaminating organisms and limited the time for breaks between cropping seasons (such that facilities could not be thoroughly cleaned or priorities relaxed) and where it was difficult to keep the facility sealed from the outside. These issues were monitored and efforts at troubleshooting were initiated with the intention of further optimizing facilities for hot tropical climates.

Development of an IPM Approach

The production and release of Trichogramma spp. was only one component of a wider IPM strategy implemented in the region. Development of the IPM strategy was based on information collected during the PRAs conducted at the start of the program, during subsequent stakeholder meetings (Fig. 4F), and from questionnaires sent to the plant protection community within each of the three target countries. There is a growing body of literature related to rice IPM, indicating that nectar plants established on rice bunds (leaves) can reduce pest populations and reduce insecticide applications while increasing grain yields (Gurr et al. 2012, 2016). Furthermore, nectar plants have been shown to increase parasitism by Trichogramma spp. of stem borer eggs in the Philippines (Vu et al. 2018, Horgan et al. 2019). Alternate wetting and drying (AWD) can reduce the incidence of pests while also conserving water and reducing greenhouse gas emissions (Chapagain et al. 2011, Hussain et al. 2015). Several other cultural control measures are known to be effective in pest management, including split fertilizer applications or harvesting rice plants at ground level (Mahuku et al. 2017). Based on this information, growing flowering plants such as sesame or soybean on the rice bunds, avoiding insecticide applications during the first 40 d after transplanting, AWD, and adherence to optimal soil nutrient management and harvesting techniques were all recommended as part of the IPM strategy. However, the key component of the strategy was the application of Trichogramma spp., biocontrol agents (3–4 releases at 100,000 wasps per ha and 100 release points/ha) (Ko et al. 2014). Therefore, taking biological control as a baseline, tailor-made guidelines that incorporated regional priorities (pest species of most concern, crop rotations, insecticide resistance status and usage policies, etc.) were developed for each of the target regions (i.e., within countries). The strategies were consolidated with the preparation of didactic guides that outlined relevant IPM measures for farmers, extension technicians, and policymakers in the principal regional languages (Chinese, Laotian, and English) (Fig. 2). The guidelines emphasized that insecticides may be used in IPM only as a last resort. However, to test that any insecticides used would be compatible with the biological control system, laboratory studies were conducted with four insecticides that target planthoppers (i.e., pyrethrin, thiamethoxam, buprofezin, and nitenpyram) to test for their toxicity to T. chilonis. All these insecticides resulted in >90% mortality of T. chilonis adults, but the effects were much less pronounced on the larval and prepupal stages developing inside striped stem borer eggs (Ko et al. 2015). Therefore, it was recommended that insecticide treatments should be avoided a week before and after the application of Trichogramma spp. wasps (Ko et al. 2015).

Capacity-Building of Farmers

A ‘Training of Trainers’ approach was used for training farmers on IPM in the target regions (Fig. 5C and D). First, about 50 IPM trainers, recruited from the national crop health extension systems, received 2 to 3 d of training on IPM from the project partners, focusing on rice and specifically on new aspects such as the use of biological control agents. Overall, nearly 50% of the IPM trainers were women with the lowest proportions in China and very high proportions in Myanmar. A training curriculum and supporting materials were jointly developed to cover IPM principles and the recommended IPM measures for each region, including how to design and implement the measures. According to the curriculum, each farmer was expected to receive five theoretical and practical sessions. However, not all of the five training sessions were implemented in all villages. Furthermore, in villages where all five were implemented, not all farmers attended each session. Nevertheless, the training helped farmers to better understand beneficial insects and other natural enemies in rice fields. Examples of natural enemies were also collected during an ‘insect zoo’ exercise (Fig. 5D). Overall, 137 training sessions reaching more than 6,400 farmers were provided in the target regions (Figs. 5E and F). Due to the substantial contribution of women to labor and decision-making in rice cultivation in the target countries, the success of extension efforts depends on reaching women as well as men. As such, a key consideration in the project was to ensure an adequate gender balance such that, overall, approximately 50% of all trainees were women. Despite the large numbers of farmers that received training, this training was probably insufficient for individual farmers to understand all the potential aspects and benefits of IPM in the rice crop and we suggest that further efforts at training, using traditional as well as novel training approaches (e.g., ICT-based communication technologies) are still necessary and might form a part of future TRF standard operations and support services.

Demonstration of IPM in the Field

Demonstration plots of approximately one hectare were set up in farmers’ fields in Laos, Myanmar, and the two Provinces in southwestern China (one plot each) with the aim of raising awareness of IPM among farmers. The plots were also designed to collect data on the efficacy of the biological control-based IPM approach (see above). Specifically, three releases of Trichogramma wasps were conducted, in line with the developed release strategy. The implementation of IPM measures and the data assessment in IPM and control fields (where conventional pest management was practiced) were conducted by project partners in the respective countries. The field plots demonstrated the advantages of IPM in irrigated rice production. Most importantly, higher rice yields (in the range of 150 kg/ha, unpublished data) were achieved in IPM plots compared to neighboring farmers’ fields that used conventional pest management practices. Furthermore, compared to farmers’ fields, insecticide inputs were reduced by about 1.5 applications in the IPM plots. Natural enemies were more abundant in the IPM demonstration plots (e.g., spiders overall about 2 times more) and pest management costs were reduced by 100–150 Euro/ha (unpublished data). Pests were more abundant in some of the IPM plots during early crop stages but were virtually always lower than in the control fields towards the end of the cropping season. This is in line with observations from other
studies that compare insecticide-free and conventional plots (Horgan et al. 2017). Higher pest numbers at early crop stages are not generally considered problematic because rice compensates for insect damage during tillering and pre-tillering stages, particularly hybrid rice varieties (Horgan et al. 2016). Farmers were generally positive about the demonstration plots and the IPM strategy because of the reduced pesticide use, increased cost-effectiveness, and increased yields.

With such generally positive results, the question may be asked: of the many millions of rice farmers in Asia, why do only a small number apply biological control? One aspect is the likely higher costs of the biological control solution. Many of the pesticides used by farmers in Asia have been on the market for a long time, are broad-spectrum, and are relatively cheap. Therefore, it is difficult for biological control to compete with chemical control in the pest management sector. To address this issue, several studies—mainly conducted in India—have assessed the costs and benefits of biological control by comparing the yields and input costs associated with Trichogramma spp. plots against those of untreated controls and/or standard farmers’ practices (e.g., Mahal et al. 2006, Sasmal et al. 2018). As with the present case study, many of these previous studies reported positive cost–benefit ratios that favor the application of biological control. These cost–benefit analyses have not included potential long-term benefits such as the wide-area recovery of natural enemy populations and benefits for human health and the environment. Further educating farmers to better understand pest and natural enemy ecology and to recognize the advantages of biological control would help farmers to appreciate the value of such Trichogramma-based pest management techniques. Demonstration plots proved an effective tool for such education.

Sustainability

Although project support ceased in 2016, there are good indicators that most of the TRFs will remain productive and that IPM adoption will increase where the TRFs are used as focal points (Babendreier et al. 2019). Despite the closure of two of the original 12 TRFs only 2 yr after the end of the project, and with two others reducing functions to only conduct stock rearing, eight are still producing substantial amounts of Trichogramma spp. wasps. These produce enough wasps to cover several hundred hectares of rice (Babendreier et al. 2019). Perhaps the greatest endorsement of the TRFs came from the regional agricultural authorities in Guangxi Province, China, that initiated their own TRFs outside the EU project. The policy environment (such as the ‘Green Control Initiative’ in China, the ‘Myanmar Rice Sector Development Strategy’ and the ‘Green Agriculture’ initiative in Laos, as well as national participation by all countries in the Convention on Biodiversity) clearly favors the IPM approach being adopted across several institutional levels. Governments in all countries and at different levels (national, provincial, and district/prefecture) are now beginning to adopt IPM and biological control and have provided continued support to the project either through human and/or financial resources, through subsidies, or by seeking external funding. At the farm level, one good indicator for sustainability in southwestern China is that farmers (especially those managing larger areas) are willing to pay for the Trichogramma spp. cards they need for their fields, provided they are not more expensive than insecticides. However, for the time being, only a few farmers in Myanmar pay for the Trichogramma spp. cards, and at prices well below production costs. Trichogramma spp. production must be more effective and thereby reduce final production costs if the TRFs are to develop into independent businesses.

Some partners have plans to expand Trichogramma spp. applications to other crops, besides rice. For example, in Xing’an County, China, the local partner PPS has already expanded the Trichogramma-based technology to other target pests in high-value crops such as grapes and sugarcane, even without considering a better-adapted Trichogramma species. In Myanmar, field studies have already begun to assess the use of T. japonicum from the TRFs against Spodoptera litura (Fabricius) in cabbage. The Trichogramma-based IPM strategy developed as part of this project has also been introduced to related CABI projects such as Plantwise (Powell 2017). This means that plant doctors (trained extension workers) have knowledge of Trichogramma spp. as a green pest control option and can recommend biological control to farmers that face lepidopteran pests in rice. However, even where recommended, the use of Trichogramma spp. is often better suited to local-area or village participation, rather than as an individual farm approach, and Trichogramma spp. cards are still often unavailable or in limited supply at the country level.

In general, the project helped to establish the human and institutional capacity of project partners required to support IPM in the GMS. Specifically, the project brought Trichogramma spp. production up to scale and allows for expansion to other areas and other crops in the future. A supporting framework for continued cooperation, participation, and learning among farmers and other stakeholders has also been put in place. For the TRFs, the strong base established by the program in the form of documents such as owner agreements, business plans, and production plans (Fig. 2), together with the built capacity (Fig. 5), will allow for the continued production of biological control agents. However, this will depend on some support from government plant protection sectors for the time being.

Raising awareness of IPM and the use of Trichogramma spp. was and will remain highly important to the sustainability of the project. By the end of the project in 2016, partners had hosted or organized over 70 different registered IPM events, and many more that were not registered. These ranged from field days, meetings with stakeholders in the plant protection sector, interviews, regional TV contributions, national newspaper articles, and other public events (e.g., at the world food day) that promoted the rice IPM project. Finally, a multi-regional symposium was implemented in association with the 2015 Chinese Biological Control Industry Annual Meeting in Wuhan, Hubei Province, China. During this event, the research outcomes of the projects were presented to a wider national and international audience, thus strengthening south-south and north-south research partnerships. Finally, results from different components of the project have been published as a range of peer-reviewed papers (e.g., papers by Babendreier et al. Guo et al. Ko et al. and Tang et al. in the accompanying references), and further papers from the project are anticipated in the coming years. Altogether, the above-mentioned aspects—from capacity building to policy support—are expected to contribute jointly and significantly towards the sustainability of the program.

Recommendations

Based on the experience gained in the GMS project, we suggest that a number of issues should be considered for effective, sustainable biological control programs. For example, the typically hot climate of countries such as Laos and Myanmar can cause problems during the Trichogramma spp. production phase and probably also in the field, e.g., mortality might be high and longevity relatively short when temperatures rise above 35°C. This will be more severe under the increasing temperatures predicted by current climate change models and it is still difficult to predict whether a given Trichogramma species, even when selected for temperature tolerance, will be able to adapt and perform under high-temperature conditions. Our climate
experiments, although they indicated sensitivity to high temperatures and rainfall, did not allow for insects to seek suitable microclimates in rice fields, which could substantially reduce climate change. Given current climatic instability and the effects of climate on pest species, it may also be challenging to meet production targets that satisfy farmers’ demands because pest incidences can change from season to season and within short time frames. This will also make it difficult for Trichogramma spp. producers to stabilize earnings, and for farmers to rely on the availability of biological control agents. A farmer survey recently conducted in Iran showed that a significant proportion of biological control adopters stopped using Trichogramma spp. as a result of similar challenges (Abdollahazadeh et al. 2017). The release of Trichogramma spp. in the hottest regions might be avoided or in areas with otherwise suitable climates, releases might be avoided during hot periods. Nevertheless, our main climate-related problems during this project were experienced in the production facilities (e.g., condensation, humidity, high temperatures, etc.). Many of these problems can be overcome by moving away from rustic production facilities towards more climate-controlled rearing conditions.

The practice of area-wide biological control is new in some of Asia’s rice-producing countries. As a consequence, many farmers and other stakeholders have only limited knowledge of high-quality biocontrol agents. Farmers expect high reliability from any plant protection product, i.e., that any given product, whether chemical or biological, has the same effect each time it is applied. Even if the quality of the Trichogramma spp. cards is high when leaving the production facility, there is potential for failure if cards are placed in the field too early or late relative to the time of wasp emergence, if placed out at the wrong time of day, or too soon after insecticide applications. Because, the effectiveness of Trichogramma spp. can vary greatly due to combinations of complex factors, such as rearing conditions, field settings, or host densities, further detailed ecological studies are required in order to achieve more consistent results (e.g., Nickel 1964, Tang et al. 2017). Farmers might also consider the technology laborious because each card has to be individually stapled to rice plants. Therefore, as long as the Trichogramma spp. cards are not cheaper than chemicals, farmer uptake of biological control may be slow. Therefore, a subsidy system and more advanced capacity building through government-supported plant health systems may be required to further promote biological control and escape the lock-in of insecticide use. Our experience during the GMS project suggests that such training programs can be difficult to design and implement, and will, therefore, also require sustained financial support (Quizon et al. 2001). The fact that China has a stronger plant health sector, compared to Laos and Myanmar, is likely a relevant factor for the overall higher success there, in terms of production of Trichogramma wasps and IPM implementation.

In summary, the GMS project demonstrated that advanced IPM systems focusing on cultural control as well as biological control have a high potential to be successful in terms of keeping pests at tolerable levels and increasing farmers’ incomes (see also Fahad et al. 2015 for a review). The GMS project reported here is the first area-wide application of biological control of any major crop pest in Laos and Myanmar, and indicates that through careful consultation and by including relevant stakeholders, even early attempts at area-wide control can have high success. Relying less on broad-spectrum insecticides in rice production is expected to increase the overall sustainability of the rice-growing ecosystem, including better management of pests such as planthoppers and leaffoppers that are difficult to control (Horgan 2017a,b). This case study also adds to an increasing number of studies to indicate that rice production systems offer some unique opportunities to reduce pesticide use and thereby improve human and environmental health (e.g., Gurr et al. 2016, Horgan 2017b).

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