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PLANT PROTECTION OUTLOOK IN THE ASIA-PACIFIC REGION

Including an in-depth view of the invasive fall armyworm



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Foreword

Agriculture underpins the livelihoods of nearly 2.5 billion farmers and is of pivotal importance in eradicating hunger, resolving malnutrition and ending poverty. In the Asia-Pacific, agri-food production is increasingly affected by climate change, extreme weather events, and the unceasing proliferation of transboundary pests and pathogens. Animal pests affect virtually all types of food crops, lowering primary productivity and degrading the quality of harvested farm produce. These biotic constraints negatively impact our ability to feed a growing human population within the limits of our planet.

Climate change makes crops more susceptible to pest attacks (invasive or endemic) and facilitates the arrival of new pests e.g. by shifting their long-distance movement patterns. Over the past years, transboundary pests such as fall armyworm (FAW), desert locusts, brown planthopper have inflicted major losses in prime food crops such as rice, corn and sorghum. Eradication of these pests is entirely unfeasible and pest-induced losses negatively impact farming communities in myriad ways. For example, since 2019, maize farmers in southern China have largely tackled FAW outbreaks by reverting to repeated spray applications of synthetic pesticides. Pesticide-based approaches aren't only costly (especially for resource-poor smallholders), but also entail risks for farmer health and the environment.

Climate-Smart Agriculture (CSA) is an integrated approach to sustain agri-food production in the face of the above biotic and abiotic adversities. The CSA toolbox includes a range of measures to raise farm efficiency, substitute chemical inputs with agroecological measures, and pursue a far-reaching redesign of farm management systems. Through harnessing functional biodiversity for transboundary pest control, certain CSA schemes lower the vulnerability of agri-food production systems to pest attack. Yet, most Asia-Pacific countries lag in their implementation of CSA practices and thereby steadily undermine the social-ecological resilience of their farming systems. In close collaboration with the Asia-Pacific Plant Protection Association (APPPC), this Plant Protection Outlook was crafted as a way to ensure that eco-friendly practices, agroecological approaches, and pest-suppressive farming systems feature prominently within CSA schemes. This report equally helps to bridge the gap between "know-how" and "do-how" approaches in the plant protection programmes and policies of various Asia-Pacific countries.

I would like to thank the Asia-Pacific Plant Protection Association network for contributing to this valuable exercise, and take the opportunity to congratulate Yubak and Kris for this eye-opening technical report. Undoubtedly, this Plant Protection Outlook will serve as a compass for future efforts to upgrade or refurbish plant protection programs in Asia-Pacific countries.

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Abbreviations and acronyms

AI	artificial intelligence
APPPC	Asia-Pacific Plant Protection Association
CSA	climate-smart agriculture
ET	economic thresholds
FAO	Food and Agriculture Organization of the United Nations
FAW	fall armyworm
FFS	farmer field school
GM	genetically modified
IPM	integrated pest management
IRM	insecticide resistance management
MoA	modes of action
NPPO	National Plant Protection Organization
NPV	nucleo-polyhedrosis viruses
TEF	Thai Educational Foundation
TPP	transboundary pests and pathogens

Executive summary

One of the world's greatest challenges is to feed a growing human population in an effective, sustainable and environmentally conscious manner. In the Asia-Pacific, agri-food production is greatly impeded by a speciose complex of transboundary pests and pathogens (TPP). Integrated pest management (IPM), a sequential decision-making process founded upon agro-ecological principles and aimed at reducing pest-induced losses with minimal (if any) reliance upon chemical toxins, is tailor-made to resolve the impact of TPP. This technical paper draws upon the results of online surveys and systematically maps the layout and inclusiveness of national plant protection programmes. It examines whether IPM is being used optimally to tackle recent invasions of the fall armyworm (FAW) (*Spodoptera frugiperda*).

Even though Asia-Pacific phytosanitary programmes are well-aligned with the IPM pyramid model, its foundational components (decision criteria, bio-ecology and biological control) are frequently overlooked. Pesticide overuse is an increasingly pressing concern in Asian countries, and the current pesticide lock-in is often ascribed to a lack of knowledge among stakeholders, inadequate policies and (alleged) immature IPM technologies. Biological control and agro-ecology deliver clear win-win social-environmental outcomes; yet, most of the perceived attributes of these nature-based approaches hamper their farm-level diffusion. Several countries have acquired credible in-house capabilities in TPP diagnostics and socioeconomics but hold rather outdated, fragmentary IPM national policies. A major overhaul of pesticide registration protocols, insecticide resistance management schemes, farmer-scientist interplay and legislative frameworks for biological control (e.g. biopesticides) is needed.

FAW made its unwelcome arrival in 2018 in the Asia-Pacific region. Countries in the region find themselves at different stages of rolling out their FAW mitigation programmes and follow a myriad of strategic directions. Some FAW-afflicted nations prioritize the on-site validation and transfer of management tools, while others proceed to outline FAW taxonomy, basic ecology and spatial distribution. Asia-Pacific countries have made less progress in defining curative or preventative control options for FAW; as a result, rates of insecticide use in Asia's maize crop have reportedly increased by 25–60 percent over a two-year period. Most nations in the region have embarked upon exciting new research on FAW egg parasitoids and entomo-pathogens. Pathways have been drawn to ensure that those countries continue within this virtuous cycle, and scale down their use of pesticides while at the same time they harness the power of agro-biodiversity for FAW control.

By juxtaposing countries' FAW programme priorities with their in-house capabilities, this technical paper puts forward several tactical interventions to fill capacity gaps, mobilize technical expertise, redraw IPM legislation and spotlight early-stage biological control successes. As such, this work provides invaluable guidance to future efforts to upscale nature-friendly technologies across the Asia-Pacific. No doubt, the net positive monetary, environmental and societal dividends of such approaches will yield enormous returns on future investments.



1. Introduction

Coping with transboundary pests under global climate change

Worldwide, animal pests and plant diseases jeopardize agricultural production, which affects food security, human nutrition, and economic prosperity and farmer livelihoods. In the absence of control measures, these biotic constraints lower crop yields by a respective 18 percent and 16 percent (Oerke, 2006). There are multiple transboundary pests and diseases. Their geographic distribution and damage to crops are routinely unconfined by national borders. More so, several pests actively disperse within and between continents while wind patterns distribute pathogens on a global scale (Brown and Hovmøller, 2002). Climate change is likely to exacerbate these phytosanitary threats and to favour a steady expansion of their distributional range (Bebber, 2015).

In the Asia-Pacific region, transboundary pests and diseases cause annually recurring losses of USD 57.6 billion and USD 43.8 billion respectively in eight major crops (Nwilene *et al.*, 2008), inflicting substantial damage on prime food crops such as rice and wheat (Savary *et al.*, 2019). For decades, endemic pests such as brown planthopper or diseases such as blast and blight have hampered rice cultivation (Bottrell and Schoenly, 2012), while the beet armyworm, diamondback moth, *Liriomyza* leafminers or the eggplant fruit-borer have reduced both harvest quality and quantity of other food security crops (Waterhouse, 1998). Yet, their incidence, severity and impact vary greatly between growing seasons, crop typologies, geographies and pest or disease taxa. For example, stem borers regularly cause losses of up to 95 percent in India and Indonesia but cause only lower rice yields of 7 percent in the Philippines (Yudelma *et al.*, 1998). Losses in primary productivity or harvest quality, however, cannot only be ascribed to endemic organisms; global trade increasingly facilitates the inter-continental spread and establishment of non-native organisms, including herbivorous pests (Diagne *et al.*, 2021).

As a result, invasive pests currently inflict agricultural losses worth USD 30 billion per year across Southeast Asia (Nghiem *et al.*, 2013) and over USD 100 billion in China (Paini *et al.*, 2016). These costs are only a fraction of the monetary gains that could be recovered in the absence of beneficial, pest-killing insects (Losey and Vaughan, 2006). Despite the monetary weight, food security implications and broader societal impacts of transboundary pests and pathogens (Burra *et al.*, 2021), regionally coordinated risk assessment, prevention and control is sorely lacking throughout the Asia-Pacific (Nghiem *et al.*, 2013).

One invasive pest of particular concern is the fall armyworm (FAW) (*Spodoptera frugiperda*) (Smith) (Lepidoptera: Noctuidae), a polyphagous herbivore with a high reproductive capacity that is endemic to the Neotropics. In its native range, FAW engages in long-distance migration and relies upon low-level jet stream currents to annually colonize cropping fields across North America (Luginbill, 1928; Johnson, 1987). Though FAW has been recorded in more than 350 host plants, it exhibits a clear preference for gramineous crops such as maize, rice and sugarcane (Montezano *et al.*, 2018) and occasionally damages such plants as Phaseolus beans, tomato and cotton (Alves de Paiva *et al.*, 2018; Wu *et al.*, 2021; Barros *et al.*, 2010). In maize, FAW can act as a cutworm in newly established crops; it feeds extensively in the whorl and its late-instar larvae also bore into the cob (Andrews, 1988; Wyckhuys and O'Neil, 2006). In 2016, FAW made its unfortunate arrival in West Africa and rapidly spread across the continent, interfering with the food supply for millions of people (Goergen *et al.*, 2016; Day *et al.*, 2017). In African maize fields, FAW-related yield losses reportedly range between 20–50 percent (Early *et al.*, 2018), though actual field observations in Zimbabwe only reveal 11.5 percent reductions (Baudron *et al.*, 2019).

In 2018, FAW invaded India's Karnataka state where it attained in-field incidence levels of up to 100 percent (Kalleshwaraswamy *et al.*, 2018; Mallapur *et al.*, 2018). By late 2019, FAW had spread across most of the Asia-Pacific region with reports from China, Republic of Korea, Nepal, Indonesia and Viet Nam (Sun *et al.*, 2019; Trisyono *et al.*, 2019; Dao *et al.*, 2020; Kathri *et al.*, 2020; Lee *et al.*, 2020). As such, FAW is expected to slash crop output in the 44 million and 12 million hectares of maize that is currently grown in eastern Asia and Southeast Asia, respectively. Model-based projections show that countries such as Australia, China, India, Indonesia, Malaysia, the Philippines and Thailand are especially vulnerable to FAW (Early *et al.*, 2018; Fig. 1). Aside from maintaining year-round viable populations in tropical (and sub-tropical) areas, FAW will rely upon seasonal monsoon dynamics to extend its spatial distribution into the Democratic People's Republic of Korea, Republic of Korea and Japan (Ma *et al.*, 2019; Wu *et al.*, 2019). In addition to the extensive damage and variable yield losses that so far have been observed, smallholders currently divert a tangible share of their farm revenue to purchase synthetic pesticides to control FAW (Yang *et al.*, 2021). Hence, it is possible that millions of Asian maize growers will face increased vulnerability to poverty and an increased (occupational) exposure to toxic chemicals due to the yearly incursions of FAW.

Given the extensive socio-economic impacts of transboundary pests, national governments need to step up their proactive management and deterrence. Pest-induced losses can be averted by an array of preventive measures (i.e. risk assessment, surveillance, tightened biosecurity and early detection), through strengthening the ecological resilience of cropping systems and by promoting cost-effective management tactics such as biological control (Bommarco *et al.*, 2013; Diagne *et al.*, 2021). For invasive and endemic pests alike, on-farm biodiversity can be harnessed to lower the rate of invasion and to kill more pests (Horrocks *et al.*, 2020). Beneficial insects have suppressed multiple transboundary pests in the Asia-Pacific over a long period (Wyckhuys *et al.*, 2020c), while agricultural diversification consistently results in win-win outcomes for pest control and crop yield (Delaquis *et al.*, 2018; Tamburini *et al.*, 2020). Also, to fortify the resilience of agro-ecosystems in the face of climate change, varietal resistance, habitat manipulation and semiochemicals show ample promise (Egan *et al.*, 2021). All these practices are core constituents of integrated pest management (IPM) (Naranjo, 2011), a globally valid decision-support system that accentuates the role of avoidance tactics in delaying or preventing a build-up of pests. Promoting these avoidance measures, however, should be accompanied by concerted efforts to discourage synthetic pesticide to avoid the emergence of secondary pests, pest resurgence and a gradual erosion of natural pest regulation (Geiger *et al.*, 2010). This is especially important in Malaysia, the Philippines, large sections of China, India's Indus Valley and Viet Nam's major river deltas; areas where elevated pesticide residues are compounded by water scarcity risks (Tang *et al.*, 2021). As farmers often find themselves unprepared to tackle invasive pests, and their use of non-chemical approaches is impeded by various obstacles (Cowan and Gunby, 1996; Upadhyay *et al.*, 2020; Bakker *et al.*, 2021), it is crucial that they become actively involved in technology development, evaluation and validation. Farmer education and awareness-raising are essential components of an effective management programme against both invasive and endemic pests.

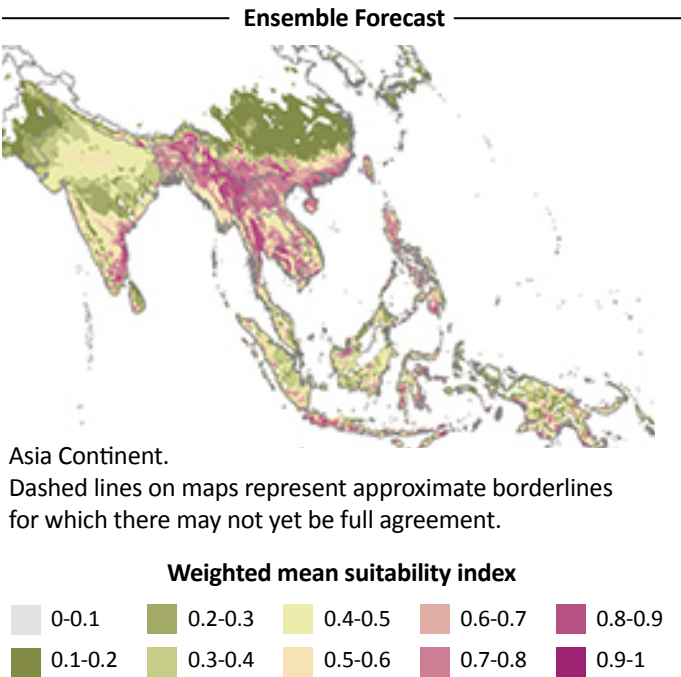


Figure 1. Potential FAW distribution across the Asian continent, as predicted by an ensemble of species distribution models (Early *et al.*, 2018). Colours ranging from dark green to dark red depict areas with increasing levels of climatic suitability.

In its native range, FAW regularly attains low infestation levels and does not require curative pest management (Morales and Perfecto, 2000; Wyckhuys and O'Neil, 2006). Particularly in smallholder systems, a build-up of the FAW population is prevented by diversifying cropping systems, conserving beneficial insects or maintaining biodiverse field surroundings. On the other hand, on intensified maize monocultures, FAW are routinely managed with insecticide sprays and sporadically managed by using genetically modified (GM) crops, biopesticides and augmented with releases of parasitic wasps (Burtet *et al.*, 2017; Figueiredo *et al.*, 2015). As a result, field-evolved resistance has been recorded for at least 40 insecticide active ingredients (AI) and *Bacillus thuringiensis* strains (Mota-Sanchez and Wise, 2021). This carries immediate implications for the effective mitigation of invasive pests in Africa and the Asia-Pacific.

Since FAW's 2016 arrival in Africa, and its subsequent invasion of Asia, a wide range of agro-ecological approaches and control tactics (chemical, biological) have been evaluated. In East Africa, intercropping with forage legumes reduced FAW damage by 87 percent as compared to maize monocrop plots (Midega *et al.*, 2018). In India, a local entomopathogenic fungi and baculovirus accounted for over 50 percent mortality of FAW larvae (Firake and Bhere, 2020). Lastly, the recent detection of the egg parasitoid *Telenomus remus* in numerous African countries opens the door for augmentative biological control, an approach that has resulted in 80–100 percent control in South America (Pomari *et al.*, 2013; Kenis *et al.*, 2019). At the same time, several Asia-Pacific countries have endorsed the use of hazardous pesticides or embraced insecticide-coated seeds, with the latter practice violating core IPM principles (Tooker *et al.*, 2017; Jepson *et al.*, 2020). While some countries have made progress in the cost-effective, nature-friendly control of FAW, others are lagging or have deployed technologies that risk degrading the long-term productivity and resilience of farmland.

Considering the continuous arrival of invasive pests, the multi-billion dollar impacts of resident pests and the progressive spread of FAW, it is time to conduct a systematic review of the plant protection programmes across the Asia-Pacific region. Such a diagnostic assessment can shine light onto the maturity, inclusiveness and implementation status of national plant protection programmes and open a window onto ongoing FAW mitigation efforts. Aside from revealing crop pests of common concern, strategic directions and programmatic priorities at an Asia-Pacific regional level, this exercise can help to pinpoint the strengths and weaknesses of individual countries in up-scaling sustainable crop protection. As such, the Food and Agriculture Organization of the United Nations (FAO) and its partners could be well equipped to tailor development assistance to the needs of countries, identify opportunities for inter-country cooperation and fill capacity gaps through specialized training courses.

2. Project methodology and data-gathering approach

In order to collect the underlying data for this report, a three-pronged approach was followed. First, two separate questionnaires were developed in February 2021 (Appendix I, II), finetuned with assistance from different FAO plant protection experts, and transferred to an online survey format. A first survey (titled “Eagle-eye view on Asia-Pacific crop protection”) aimed at conducting a systematic review of the plant protection programmes that are currently in place within each of the Asia-Pacific nations. It is an approximately 30–45 minute survey intended to capture the thematic foci, management strategies and relevant policies of plant protection programmes across the Asia-Pacific. Survey respondents were invited to elaborate on priority pests/diseases, strategic directions within their country’s IPM programme, the degree of attention that is currently given to themes such as basic/applied science and participatory research, and the status/reach of their farmer education programmes. A separate section within the questionnaire equally intended to gauge the perspectives of the respondents on different topics, such as pesticide-centered crop protection versus biological control, and top-down versus bottom-up extension approaches. Lastly, a set of questions aimed at identifying different barriers to the uptake and diffusion of biological control, such as inadequate legislation, lagging IPM science and improper farmer education. A second survey (titled “Feeling the pulse of FAW mitigation programmes”) was intended to critically assess the maturity, inclusiveness and implementation status of national FAW mitigation programmes. It is an approximately 30–45-minute online survey aimed at gauging the thematic foci, management strategies and relevant policies of the FAW mitigation programme of a sub-set of Asia-Pacific countries. In the first section, respondents were invited to elaborate on the spatial extent, severity and livelihood impacts of recent FAW outbreaks. Subsequent sections aimed to gain in-depth insight into country-level priorities regarding: 1) FAW identity, biology and ecology; 2) monitoring and field scouting; 3) FAW prevention and control; 4) farmer extension and participatory research; and 5) policy and regulation. On each of the topics, respondents were encouraged to describe strategic directions, implementation progress and the extent of in-country (scientific) expertise. Also, respondents were asked to consider the eventual obstacles in the way of sustainable FAW management and of farmers adopting IPM or biological controls to use against this newly invasive pest.

Using Survey Monkey (www.surveymonkey.com) as a cloud-based survey platform, the two questionnaires were circulated among different groups of target respondents. During mid-February 2021, the first survey was distributed among representatives of the 25 national plant protection organizations that constitute the FAO-hosted Asia Pacific Plant Protection Commission (APPPC). The second survey was shared in late-February 2021 with the FAW focal points of Cambodia, Indonesia, Nepal and the Philippines. These countries feature within FAO Global Action for FAW either as a demonstration country (the Philippines) or as a pilot country within the Southeast Asia and South Asia eco-zone. For the first survey, respondents were allowed 2–3 weeks to complete the online questionnaire. For the second survey, a follow-up (virtual) workshop was held with the relevant staff from the plant protection departments of any of the four countries. This workshop was used to troubleshoot the FAW-specific survey and to address any questions from national counterparts.

If and where relevant, the online survey approach (carried out over February and March 2021) was complemented with data from national baseline surveys coordinated by FAO’s Global Action for FAW. These studies were outsourced to the Thai Educational Foundation (TEF) between April and November 2020. Lastly, on specific topics such as country-level FAW occurrence, incidence and pesticide control, literature resources were consulted.

3. Eagle-eye view on Asia-Pacific plant protection

Overall programmatic focus

For a given country, the online survey captured its plant health targets, their (perceived) socio-economic relevance, key features of the national crop protection programme and their respective alignment with the IPM conceptual model. Eight Asia-Pacific countries provided a full or partial listing of the most pressing pest and disease issues (and related priority targets) that were addressed by their plant health programme.

Twenty-three different plant diseases were enumerated (Table 1), 6, 11 and 5 of which were associated with

bacterial, fungal and viral pathogens. Among these, 42 percent were key biotic constraints of cereal crops, such as rice, wheat, barley or corn. Transboundary diseases and causal pathogens that were listed by multiple countries included rice blast fungus (*Magnaporthe grisea*), rice bacterial blight (*Xanthomonas oryzae* pv. *oryzae*), wheat yellow rust (*Puccinia striiformis* f. sp. *tritici*), potato late blight (*Phytophthora infestans*), Panama disease (*Fusarium oxysporum* f. sp. *cubense*) and citrus greening disease (*Candidatus Liberibacter* spp.). The latter disease is caused by an insect-vector plant virus (transmitted by at least one endemic species of psyllid) and is of mutual concern to plant pathologists and entomologists.

Table 1. Common plant disease targets and priority foci, as enumerated by different Asia-Pacific countries. Diseases are indicated with their common name. The full list is drawn based upon (complete or partial) inputs from eight countries: China, Indonesia, Malaysia, Myanmar, Nepal, the Philippines, Singapore and Thailand.

Taxonomic classification	Disease	Main host	Number of reports	Number of priority targets
Bacteria: Achleplasmatales	Maize bushy stunt phytoplasma	Corn	I	I
Bacteria: Burkholderiales	Bacterial panicle blight	Rice	I	I
Bacteria: Burkholderiales	Bacterial wilt	Potato, vegetables	I	
Bacteria: Rhizobiales	Citrus greening disease	Citrus	III	I
Bacteria: Xanthomonadales	Black rot	Vegetables	I	
Bacteria: Xanthomonadales	Rice bacterial blight	Rice	II	II
Fungi: Cantharellales	Wheat sharp eyespot	Wheat	I	
Fungi: Cantharellales	Dry root rot	Sesame	I	I
Fungi: Capnodiales	Corn grey leafspot	Corn	I	I
Fungi: Capnodiales	Citrus leafspot	Citrus	I	I
Fungi: Hypocreales	Fusarium head blight	Wheat, rice, barley	II	I
Fungi: Hypocreales	Panama disease	Banana	II	II
Fungi: Magnaporthales	Rice blast fungus	Rice	IIII	III
Fungi: Peronosporales	Downy mildew	Multiple crops	I	
Fungi: Pucciniales	Coffee rust	Coffee	I	
Fungi: Pucciniales	Wheat yellow rust	Wheat	II	I
Fungi: Peronosporales	Potato late blight	Potato	II	I
Protists - Plasmodiophorales	Clubroot	Vegetables	I	I
Virus - Geminiviridae	Chili leaf curl disease	Vegetables	I	I
Virus - Geminiviridae	Cassava mosaic virus	Cassava	I	
Virus - Martellivirales	Citrus tristeza virus	Citrus	I	
Virus - Ortervirales	Tungro virus	Rice	II	I
Virus - Reovirales	Rice ragged stunt virus	Rice	I	

Similarly, 55 animal species (or genera) were listed as economically relevant pests (Table 2). Among these, 51 different species of insect herbivores (6 orders) were enumerated – with Lepidoptera and Hemiptera containing most of the pestiferous organisms. Though 11 different herbivores affected rice, the overall range of afflicted crops included a myriad of (perennial) fruits, vegetables, root and tuber crops, and livelihood security crops such as coconut, coffee or cocoa. Target pests included endemic organisms such as *Eriophyes litchi* (litchi mite) or *Nilaparvata lugens* (brown planthopper), notorious cosmopolitans such as *Bemisia tabaci* (silverleaf whitefly) or *Plutella xylostella*

(diamondback moth), and invasive species such as *Tuta absoluta* (tomato pinworm) or *Neoleucinodes elegantalis* (eggplant moth). Several of the invasive species (e.g. the recently arrived *T. absoluta* and *Spodoptera frugiperda*) are of Neotropical origin. Transboundary pests of concern to multiple Asia-Pacific countries include *S. frugiperda*, *N. lugens*, Asian corn borer (*Ostrinia furnacalis*), striped rice stem borer (*Chilo suppressalis*) and a speciose complex of *Bactrocera* sp. fruit flies. Lesser degrees of attention go to *T. absoluta*, *P. xylostella*, *Liriomyza* sp. leafminers, beet armyworm (*Spodoptera exigua*) and rats.

Table 2. Common herbivorous pest targets and priority foci, as enumerated by different Asia-Pacific countries. Pests are indicated with their scientific name. The full list is drawn based upon (complete or partial) inputs from eight countries: China, Indonesia, Malaysia, Myanmar, Nepal, the Philippines, Singapore and Thailand.

Taxonomic classification	Pest species	Main host	Number of reports	Number of priority targets
Acari: Trombidiformes	<i>Eriophyes litchi</i>	Litchi	I	
	<i>Tetranychus spp.</i>	Multiple crops	II	
Insecta: Coleoptera	<i>Cosmopolites sordidus</i>	Banana	I	
	<i>Dorylus orientalis</i>	Potato	II	II
	<i>Dorysthenes buqueti</i>	Sugarcane	I	
	<i>Phyllophaga spp.</i>	Maize	I	I
	<i>Rhynchophorus ferrugineus</i>	Coconut	I	I
	<i>Sternonchetus frigidus</i>	Mango	I	I
	<i>Xylotrechus quadripes</i>	Coffee	I	
Insecta: Diptera	<i>Bactrocera spp.</i>	Fruits, vegetables	IIIIII	IIII
	<i>Liriomyza spp.</i>	Potato, vegetables, legumes	II	I
	<i>Procontarinia sp.</i>	Mango	I	I
Insecta: Hemiptera	<i>Aphis fabae</i>	Potato, vegetables, legumes	I	
	<i>Aspidiotus destructor</i>	Orchard crops	I	
	<i>Bemisia tabaci</i>	Vegetables	II	
	<i>Cicadella viridis</i>	Rice	I	
	<i>Dalbulus maidis</i>	Corn	I	
	<i>Drosicha mangiferae</i>	Mango	I	
	<i>Ferrisia virgata</i>	Orchard crops	II	
	<i>Holotrichia spp.</i>	Sugarcane, legumes	I	
	<i>Myzus persicae</i>	Potato, vegetables	I	
	<i>Nephotettix spp.</i>	Rice	I	
	<i>Nilaparvata lugens</i>	Rice	IIII	IIII

3. EAGLE-EYE VIEW ON ASIA-PACIFIC PLANT PROTECTION

Taxonomic classification	Pest species	Main host	Number of reports	Number of priority targets
Insecta: Hemiptera	<i>Phenacoccus madeirensis</i>	Orchard crops	I	
	<i>Phenacoccus manihoti</i>	Cassava	I	
	<i>Pseudococcus jackbeardleyi</i>	Orchard crops	I	
	<i>Rhopalosiphum padi</i>	Wheat, barley	I	
	<i>Sitobion miscanthi</i>	Wheat	I	
	<i>Schizaphis graminum</i>	Wheat, pearl millet	I	
	<i>Sogatella furcifera</i>	Rice	I	I
	<i>Idioscopus clypealis</i>	Mango	I	
Insecta: Lepidoptera	<i>Chilo suppressalis</i>	Rice	III	
	<i>Cnaphalocrocis medinalis</i>	Rice	I	I
	<i>Conopomorpha cramerella</i>	Cocoa	I	I
	<i>Eudocima phalonia</i>	Citrus, perennial fruits	I	
	<i>Helicoverpa armigera</i>	Corn, vegetables	I	I
	<i>Keiferia lycopersicella</i>	Tomato	I	I
	<i>Leucinodes orbonalis</i>	Eggplant	I	II
	<i>Leucania loryi</i>	Rice, corn, wheat	I	
	<i>Mythimna separata</i>	Rice, sorghum, corn	I	
	<i>Neoleucinodes elegantalis</i>	Tomato, eggplant	I	I
	<i>Opisina arenosella</i>	Coconut	I	
	<i>Ostrinia furnacalis</i>	Corn	III	II
	<i>Plutella xylostella</i>	Cabbages	II	II
	<i>Scirpophaga incertulas</i>	Rice	I	I
	<i>Scirpophaga innotata</i>	Rice	I	I
	<i>Spodoptera exigua</i>	Potato, legumes, vegetables	II	II
	<i>Spodoptera frugiperda</i>	Corn	IIIIIIII	IIIIIIII
	<i>Spodoptera litura</i>	Cotton, vegetables	II	
	<i>Tuta absoluta</i>	Tomato	II	II
	<i>Virachola isocrates</i>	Orchard crops	I	
	<i>Locusta migratoria</i>	Multiple crops	I	
Insecta: Orthoptera	<i>Thrips palmi</i>	Vegetables	I	I
Insecta: Thysanoptera	<i>Ratus spp.</i>	Rice	II	II
Mammalia: Rodentia	<i>Meloidogyne spp.</i>	Multiple crops	I	
Nematoda: Tylenchida	<i>Idioscopus clypealis</i>	Mango	I	

Overall, survey respondents had difficulty estimating the extent to which pests and diseases affect crop yield and farm-level expenditures for pest control. On average, biotic constraints were thought to cause 20–35 percent yield losses. Respondents believed that this translated to a monetary loss between USD 300 (staple crops, China) and USD 5 000 per hectare and year (Malaysia), plus expenditures for pest control that ranged from USD 25–50 (Nepal) to USD 2 250 per hectare and year (shallot, Indonesia). In Cambodia, farm-level expenditures for pest control were thought to range between USD 40–50 per hectare for dry-season rice and USD 180–200 per hectare for vegetables. Respondents from 11 Asia-Pacific countries ranked the socio-economic impacts of transboundary pests and pathogens (TPP) fairly high, at 59 ± 33 on a scale from 0 to 100 ($\bar{x} \pm SD$; 100 being major impacts). However, countries did vary greatly in their perceptions, with Thailand (ranking 11) and Brunei Darussalam (12) perceiving crop pests or diseases to be of limited importance. Conversely, Nepal and Malaysia assigned a value of 100 to TPP threats – thus underlining their major socio-economic impacts.

All respondents (ten countries) confirmed their familiarity with the IPM concept. When asked to freely describe key features of their crop protection programme, they paid equal degrees of attention to different IPM constituent components (Figure 2). Chemical control was free-listed by six (out of nine) countries, pheromone-based trapping and

surveillance by five countries and avoidance tactics (varietal resistance, biological or cultural control) by four to five countries. Overall, the role of stakeholder education was disregarded as only two countries free-listed this component.

The general layout of Asia-Pacific crop protection programmes was well-aligned with the IPM conceptual model or so-called IPM pyramid (Figure 2). Across ten countries, varietal resistance, sanitation and cultural control, and sampling were reported to be cornerstones of national IPM programmes. While the evaluation of pesticide efficacy received priority attention (ranking 16/20), national programmes largely ignored devising the necessary tools and decision-criteria to ensure that their farm-level use is also rational, targeted and economically justified. Furthermore, within the bundle of IPM avoidance tactics, scant attention was paid to bio-ecology, landscape management and biological control. These components make up the foundation of IPM decision-making schemes and they are essential to devising sustainable TPP mitigation strategies.

Programmatic priorities differed greatly between individual countries – certain countries proved to be more technocentric, while others favoured ecologically based avoidance strategies. For instance, Nepal prioritized cultural practices and mechanical control. In contrast, Thailand placed the most weight on selecting efficacious pesticides and varietal resistance.

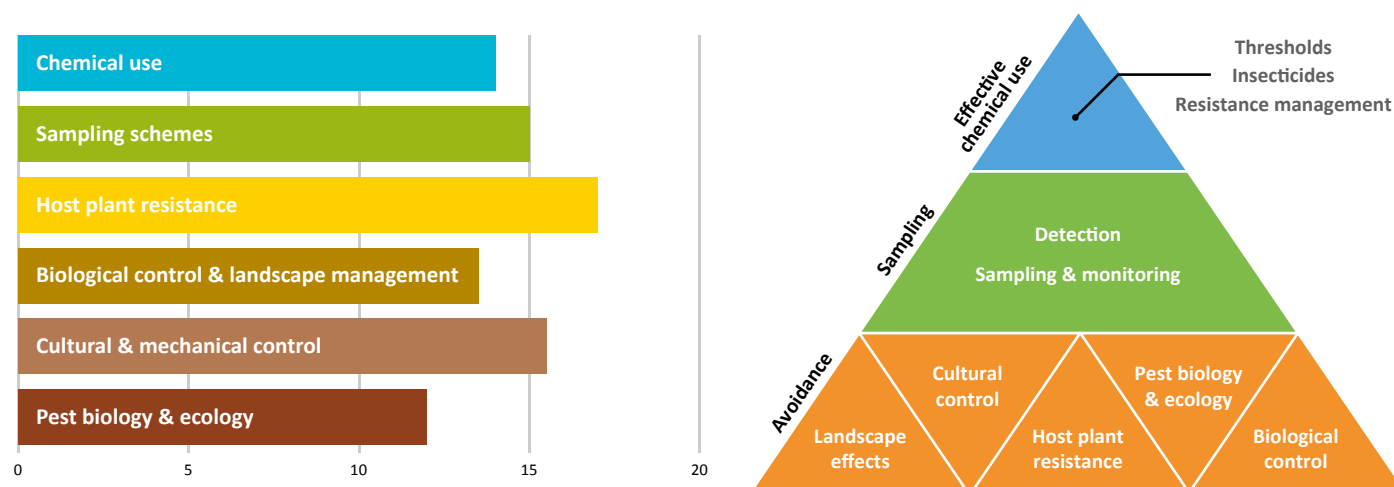


Figure 2. Overall layout of national plant health programmes as compared to the global IPM conceptual model (Naranjo, 2011). The left panel depicts the average degree of attention given to various IPM components by ten Asia-Pacific countries. The size of a given bar mirrors the relative importance of the associated IPM component within countries' current pest management programmes. The right panel shows the major IPM components and their inter-relationships, illuminating how chemical use is to be pursued as a measure of last resort, that is, when the full repertoire of avoidance tactics and non-chemical solutions fails.

Pest management behaviour of farmers

As first responders to TPPs, farmers are habitually hit hardest by irrational, ineffective or unsafe management practices. Throughout the Asia-Pacific, agri-food production is largely dominated by resource-poor smallholder farmers, with China and India jointly representing two-thirds of the world's farms. In countries such as Myanmar, Viet Nam or Indonesia, roughly 11 million, 20 million and 37 million people respectively are actively involved in farming (FAOSTAT, 2021). Daily, tens of millions of Asian farmers face TPP issues, suffer pest-induced crop losses and carefully weigh their options in terms of sustainable pest management. Yet, a swelling body of international publications signals how their management practices are dramatically misguided. Present-day vegetable growers in Viet Nam overspend by USD 330/ha/cycle on pesticides and Bangladeshi eggplant producers apply a staggering 150–200 chemical sprays per year (Pretty and Bharucha, 2015; Schreinemachers *et al.*, 2020). This is also mirrored in countries' pesticide import dynamics, which are subject to annual growth rates of 61 percent for Cambodia, 55 percent for the Lao Peoples' Democratic Republic, and 10 percent for Viet Nam (Schreinemachers *et al.*, 2017). Over the past two decades, Indonesia's pesticide imports have risen 50-fold (see also Thorburn, 2015).

Respondents from eight Asia-Pacific countries unanimously indicated how pesticide use has become a central pillar of farmers' crop protection activities. To a far lesser extent, they are also thought to use biological control and biopesticides (five countries), cultural control, e.g. adapted planting dates, row spacing or fertilizer use (five), pest-resistant varieties (three) and sanitary measures, e.g. clean seed or planting material (two). Lastly, farmers are thought to lag in adopting IPM components such as landscape or habitat management, field-level scouting and trapping, and semiochemical applications. Nevertheless, survey respondents from all countries agreed that their respective farmers did employ IPM. In Nepal and Singapore, the farmers' management toolbox consisted solely of pesticides and one additional component; yet, local farmers were still resolutely labelled as IPM-adopters. Hence, one wonders whether IPM is properly understood by decision-makers or has been diluted since its original conceptualization and is now being re-framed as integrated pesticide management (Ehler, 2006).

Globally, rates of IPM adoption are lagging while pesticide-centered approaches continue to proliferate (Bernhardt *et al.*, 2017; Hedlund *et al.*, 2020). In the pursuit of sustainability transitions, e.g. towards non-chemical pest prevention or agro-ecological practices, various socio-technical factors can hinder progress (Loorbach *et al.*, 2017). Respondents from nine Asia-Pacific countries ranked seven key socio-technical pillars in terms of their relative importance as IPM transition obstacles (Figure 3). Countries unanimously assigned the highest ranking to a knowledge pillar, thus inferring how the insufficient knowledge of farmers, plant protection officers and extension personnel and/or a deficient understanding of agro-ecosystem dynamics hamper IPM adoption. Other important pillars were those of policy, user preferences and the apparent proliferation of immature or inadequate IPM technologies. In terms of user preferences, this captures stakeholder attitudes towards certain pests or crop protection measures, peer pressure or farmers' risk-averse behaviour. This factor does, however, relate to some degree to the insufficient knowledge of farmers and their lack of familiarity with effective, non-chemical alternatives (Gent *et al.*, 2011; Wyckhuys *et al.*, 2019; Mohring *et al.*, 2020). On the other hand, only 30 percent of country respondents deemed that agro-chemical industry interference posed a major hurdle in the IPM diffusion process, contrary to Folke *et al.* (2019) or Goulson (2020), for example.

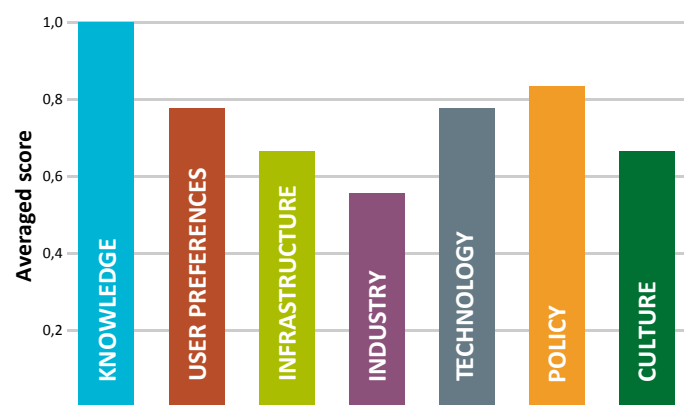


Figure 3. Perceived importance of seven key pillars within the socio-technical regime (Loorbach *et al.*, 2017) as obstacles to IPM diffusion. The relative importance of each pillar is ranked by nine Asia-Pacific countries, with the graph depicting its averaged patterns rescaled from 0 to 1.

Respondents varied greatly in their assessment of farmers' pest management practices and the extent of pesticide over-use in their respective countries (Figure 4). Though farmers' plant protection practices were ranked favourably at 63.0 ± 21.2 ($\bar{x} \pm SD$; scale of 0–100), all Asia-Pacific countries expressed concern about the degree of pesticide use (ranked at 68.1 ± 25.9 ; scale of 0–100). Countries such as Nepal, the Philippines, Indonesia and Singapore perceived farmers' management practices to be defective, while Viet Nam gave its farmers a score of 90 out of 100. Thailand, Malaysia and Cambodia perceived clear issues with pesticide over-use among farmers in their countries. These concerns are warranted, as Malaysia has the 13th highest pesticide use intensity

levels worldwide, at 7.7 kg/ha per year (FAOSTAT, 2021). China, Viet Nam and Thailand are marked by similarly high levels of pesticide use – assuming the respective 23rd, 40th and 47th positions globally. Hypothetically, there should be ample room to reduce the use of agrochemicals where the pest management practices of farmers are deemed to be faulty and pesticide over-use issues are acknowledged. As such, Cambodia, Malaysia and Indonesia could prove to be fertile ground for renewed IPM promotion campaigns. Initiating IPM transitions in China, Viet Nam or Nepal could potentially be more challenging. However, in Nepal, farmers' practices are possibly seen as faulty (or outdated) because of their ecologically centered, non-chemical nature.

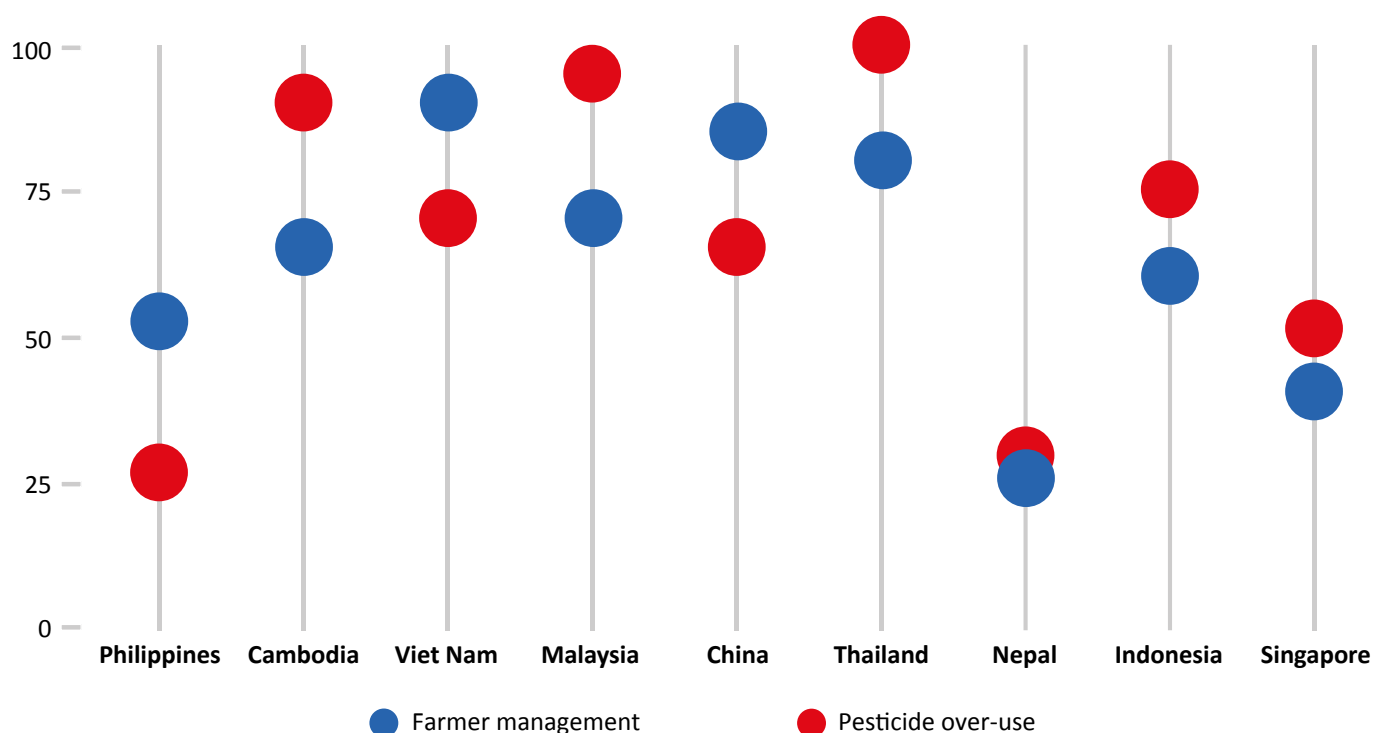


Figure 4. Country-level perceptions regarding the pest management practices of farmers and the extent of pesticide over-use. Patterns are plotted for nine different Asia-Pacific countries. Both variables are ranked on a scale from 0 to 100, with 100 either reflecting very good management or significant over-use.

Several of the patterns in Figure 4 were corroborated when individual countries free-listed options to improve or upgrade farmers' management. In terms of desired improvements, themes such as decision-support tools (three countries), pesticide reduction (three), non-chemical crop protection (two) and pest detection or diagnostics (two) were most often put forward. To achieve this, the Philippines and Singapore suggested bolstering capacity building and re-igniting farmer field school (FFS) style participatory, experiential learning. In countries such as China and Nepal, respondents emphasized (need-based) pesticide applications, personal protective equipment and in-depth training covering different AIs, dosage and application modes.

While all nine countries agreed that IPM was widely implemented (see above), only five countries believed that their farmers were sufficiently well-equipped to adopt sustainable pest management. Among five pest management domains, Asia-Pacific farmers were thought to be knowledgeable about sanitary practices (average ranking 72/100) and pest-resistant varieties (67/100). Similarly, farmers reportedly had some understanding of biological control (56/100) but a poor appreciation of economic thresholds and sampling methods (both 33/100). On the latter two topics, 30 percent of countries signaled that their local farmers were at a complete loss. On biological control, only farmers in the Philippines were believed to possess advanced levels of knowledge. Good farmer practice was ascribed to comprehensive training programmes (Malaysia) and a close collaboration with pest observers and extension officers (Indonesia).

All nine Asia-Pacific countries recognized a need for well-designed, comprehensive farmer education schemes. The IPM training programmes that are currently in place have a broad reach and cover approximately 10 000, 10 000–20 000, 20 000, and >10 million farmers in Cambodia, Malaysia, Nepal and China, respectively. These include hands-on activities and static workshops on various topics such as pesticide use, biological control and sustainable farming techniques. FFS-style initiatives make up a varying share of agricultural extension programmes, reportedly covering between 2–5 percent (Malaysia, Nepal) and 100 percent of all trained farmers (Cambodia, China). In other countries, farmer training programmes are relatively small (Viet Nam), have recently been downscaled (the Philippines) or follow a more hands-off approach, for example, by distributing leaflets (Singapore). Fewer than half the countries pursued the active involvement of women in IPM training activities, but those that did designed their programmes accordingly. This was not the case in Thailand, where respondents opposed adapting training materials to the needs of female farmers.

Prevailing perceptions and (institutional) stances

Though the overall layout of national plant health programmes was well-aligned with the IPM conceptual model (section 3 – Overall programmatic focus), some countries were more inclined to favour pesticide-centered approaches than others. This can either be ascribed to external influences (industry lobbying, funding streams) or to misguided perceptions among key decision makers. For a better appreciation of the prevailing attitudes among plant protection staff (and broader institutional stances), respondents were asked to design their own ideal IPM programme. Contrary to the actual programmes that are currently in place (Figure 2), chemical use received considerably less attention (Figure 5). While pesticide efficacy screening was prioritized in existing plant health programmes, this component was invariably downscaled (ranked 2.6/10) in respondents' depiction of an ideal IPM programme. Moreover, priority components in such a model IPM programme were varietal resistance (ranked 8.4/10), cultural control and sanitation (7.4), pest detection and sampling (7) and mechanical control (6.1). Respondents further recognized the value of characterizing pest biology and ecology (6). Although plant protection staff are well aware that avoidance measures constitute the foundation of IPM, these practices are diluted under real-world conditions. Along the same lines regarding chemical control, the model IPM programmes emphasized application thresholds and

decision criteria (4.9). Given that these elements barely feature in existing programmes and remain unknown to farmers, other (external) factors likely prevent them from receiving the attention they are warranted. Lastly, though biological control and biopesticides were allotted more attention (5.3) than any of the three pesticide-related components (1.9–4.9), this is not mirrored in current legislative frameworks, public sensitization or in farmer practice.

Individual countries differed in their depiction of a model IPM programme (Figure 6). China, Indonesia, the Philippines and Thailand all perceived IPM to be a sequential pyramidal approach with major emphasis on non-chemical avoidance measures. While China and the Philippines placed relatively more weight on pest detection and diagnostics, the other two countries considered pest biology/ecology to be the foundation of robust IPM schemes. Malaysia, and to some degree Nepal, placed comparatively more emphasis on effective chemical control and downplayed the importance of habitat management, for example, thereby tilting the IPM pyramid (Figure 6). Yet, it is encouraging to see how Malaysia assigned the highest ranking to application thresholds and decision criteria in its envisioned ideal IPM programme.

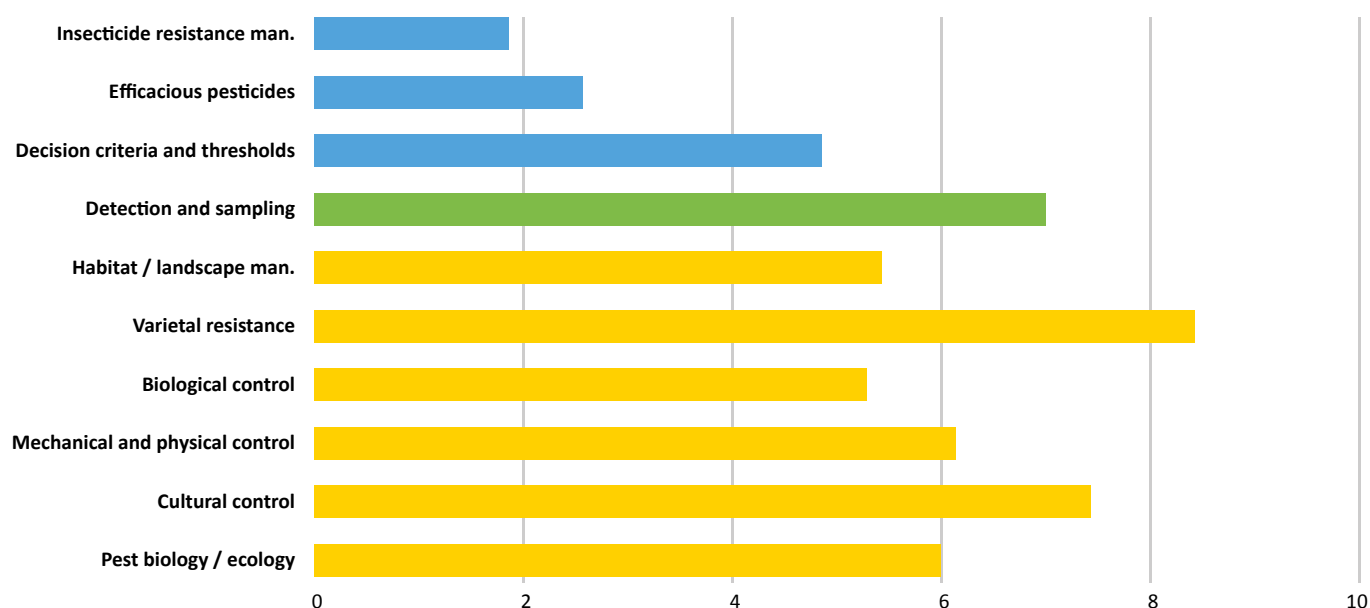


Figure 5. Overall layout of an ideal IPM programme, as envisioned by respondents from seven Asia-Pacific countries. Individual management components are ranked in accordance with the IPM conceptual model or so-called pyramid (Figure 2). For each component, the length of the bar mirrors the relative degree of attention that it warrants within a comprehensive IPM programme. Colour-schemes reflect whether components constitute avoidance tactics (yellow), sampling (green) or effective chemical use (blue).

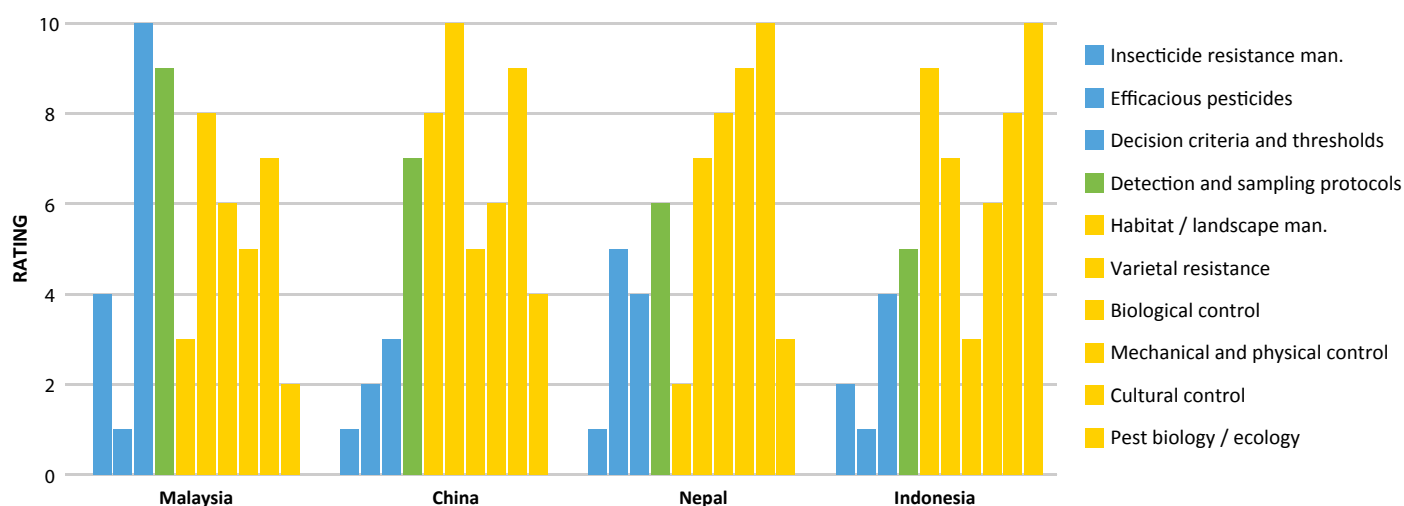


Figure 6. Depiction of model IPM programmes within four Asia-Pacific countries. Individual components are ranked in accordance with the so-called IPM pyramid (Figure 2). For each component, the length of the bar mirrors the relative degree of attention that it warrants within a robust plant protection programme. Colour-schemes reflect whether individual components constitute avoidance tactics (yellow), sampling (green) or effective chemical use (blue).

Across the Asia-Pacific, the actions of farmers are routinely perceived as a key determinant but also an immediate solution to TPP outbreaks. Nine countries elaborated on how farmers can trigger pest or disease outbreaks through irrational pesticide use (6 countries), lack of sanitary practices or contaminated seed (4), improper timing or spacing of crops (3), mono-cropping (2) and by abstaining from regular field scouting (3). All countries, except for Cambodia, saw ample value in a closer, two-way farmer-scientist interaction to resolve some of these issues. By doing so, respondents were confident that TPP impacts could be effectively mitigated while curtailing pesticide use by 37.5 ± 33.4 percent ($\bar{x} \pm \text{SD}$) nationwide. Plant protection staff in Malaysia and the Philippines deemed 50–100 percent pesticide reductions to be feasible. These kinds of reductions may be entirely realistic, given that FAO's FFS programmes attained insecticide cuts in rice in Indonesia by 61 percent, rice in Viet Nam by 82 percent, eggplant in Bangladesh by 80 percent and cotton in India by 78 percent (Van den Berg and Jiggins, 2007). In terms of crops, respondents identified 11 individual commodities as low-hanging fruit for input reduction initiatives, and suggested rice (paddy), vegetables, maize, tropical fruits and potato suggested as target crops.

Alternatives to synthetic pesticides are biological control and preventative measures such as sanitation and cultural control. Their respective on-farm adoption

and community-wide diffusion is shaped by different technological characteristics. In his landmark 1962 book *Diffusion of Innovations*, sociologist Everett Rogers indicates that how individuals perceive five technology attributes predicts their ultimate uptake, that is, their relative advantage, compatibility, complexity, observability and trialability. Respondents from across the Asia-Pacific did not consider biological control (and biopesticides) as presenting any marked disadvantage (or advantage) over synthetic pesticides (Figure 7). Yet, biological control was felt to be less compatible, observable or trialable, and more complex. These four attributes make it comparatively less likely to succeed and attain broad-scale adoption. Also, the adoption of biological control can occasionally be constrained by its availability and affordability, for example by resource-poor smallholders (Wyckhuys *et al.*, 2018; Constantine *et al.*, 2020). Recognizing these limitations and carefully assessing them within a diffusion-of-innovations framework can help bridge the research-practice gap for biological control, eventually increasing its odds of adoption. Similarly, preventative innovations such as agro-ecology tend to diffuse slowly due to the delayed rewards for farmers who are early adopters. Aside from changing the perceived attributes of pest prevention strategies, one can engage so-called champions to promote them, alter the norms of the relevant social system, wield entertainment/education or mobilize peer networks to aid their diffusion (Rogers, 2002).

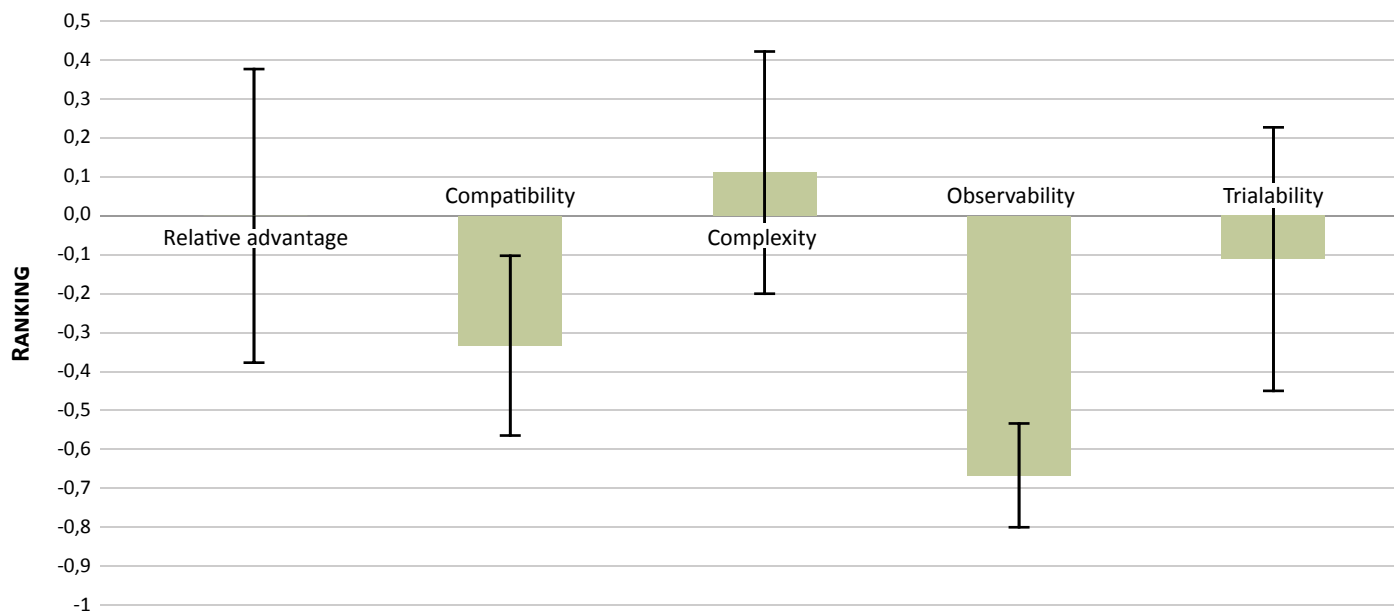


Figure 7. Comparative ranking ($\bar{x} \pm SE$) of biological control in terms of Rogers's five innovation attributes. For each attribute, respondents from nine Asia-Pacific countries rank the performance of biological control and biopesticides as compared to synthetic pesticides. Positive values reflect how biological control innovations are perceived to outperform pesticide-based approaches. Attributes are described in further detail in Appendix III.

Much is to be gained by raising the adoption rates of agro-ecological tactics and by curbing agrochemical inputs. For five socio-economic and planetary-health outcomes, respondents from nine Asia-Pacific countries routinely perceived biological control to be more advantageous than chemical control. On a scale from -2 to 2 (2 being noticeably better), biological control ranked 1.9 ± 0.3 ($\bar{x} \pm SD$) for three different themes (biodiversity conservation, human health, clean water). In terms of food safety, biological control ranked 1.6 ± 0.5 and thus equally outperformed pesticide-based approaches. By systematically documenting and communicating these diverse societal benefits (e.g. Bale *et al.*, 2008; Wyckhuys *et al.*, 2020a; Burra *et al.*, 2021), it is possible to reach a tipping point in upscaling biological control. This has the potential to enable transformative change, with non-chemical pest management becoming the norm instead of the exception.

Crop protection science and innovation

One prime feature of a country’s plant protection programme is the extent to which it effectively weds science (basic, applied) to farmer education, technology transfer and behaviour change. At present, crop protection science in nine Asia-Pacific countries receives slightly less attention than other science, technology and innovation fields (ranked -0.6 ± 0.9 on a scale from -2 to 2) with this pattern most pronounced in Singapore. Countries reportedly held credible domestic scientific capabilities in the domains of pest/disease diagnostics, pesticide efficacy screening and socioeconomics (Figure 8).

Among these countries, scientific capabilities, however, differed substantially. Across eight priority domains, Thailand (ranked 13/16) and China (10/16) proved most confident about their in-house scientific capabilities. Both countries signaled that they possess robust capacity in the fields of pest/disease diagnostics and taxonomy. On the other hand, Nepal, Singapore and Cambodia (ranked 4–5/16) considered that their crop protection science programmes were highly deficient. Among eight scientific domains (Figure 8), Thailand reportedly possessed robust capacity in all domains except for pest/disease epidemiology, bio-ecology and socioeconomics.

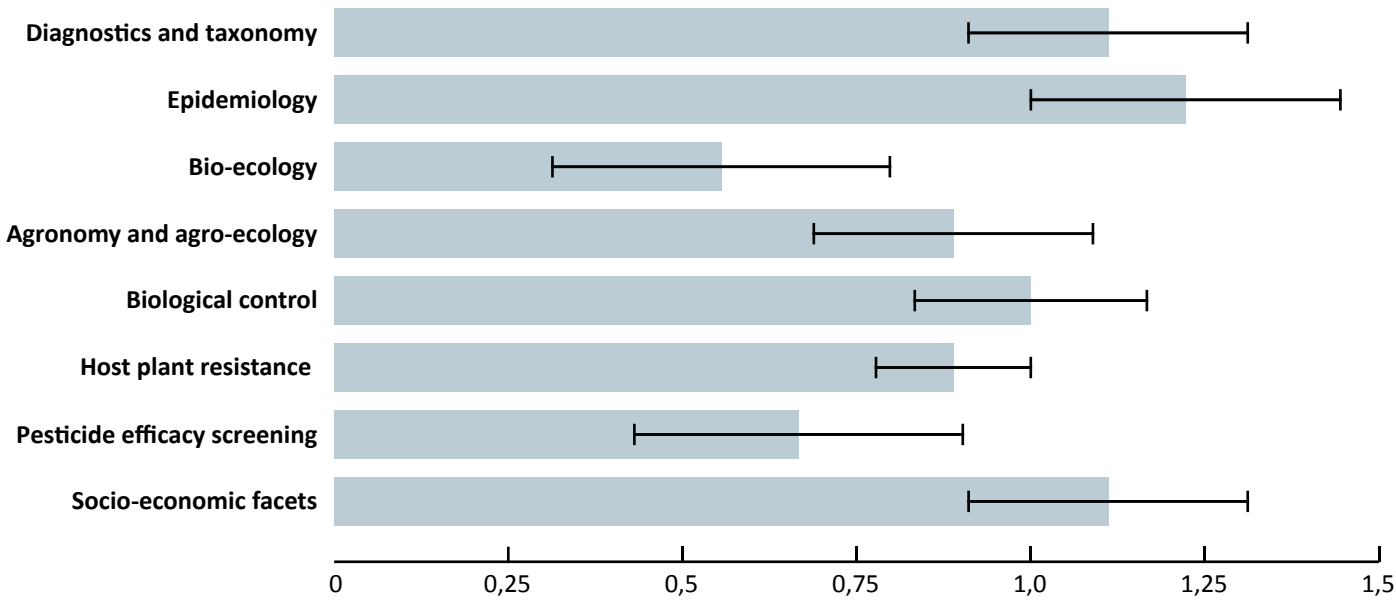


Figure 8. Domestic scientific capability in different plant protection domains, self-assessed by respondents from nine Asia-Pacific countries. For each of eight key domains, average patterns ($\bar{x} \pm SE$) are plotted and reflect overall in-country capacity on a scale from 0 to 2 (with 2 being robust capacity).

These domestic scientific capabilities relate to the interests and strategic directions of a range of stakeholders (national or local government, academia), but can equally mirror funding availability. Across the Asia-Pacific region, crop protection science was deemed to be critically underfunded. Four (out of nine) countries signaled how all eight scientific domains faced serious funding shortages. Countries proved least pessimistic regarding the funding status of biological control (ranked 0.7 ± 0.9 on a scale of 0–2) and varietal resistance (0.6 ± 0.5). Among the eight key domains, least funding was thought to be available for pest/disease epidemiology (0.3 ± 0.5). China, Indonesia and Malaysia proved least

pessimistic on long-term funding prospects. Across countries and domains, public sector contributions and international development assistance made up a respective 81 percent and 17 percent of primary funding streams. In two countries, private sector funds were most important for pesticide efficacy testing. Also, development aid was regularly mobilized for the domains of pest/disease diagnostics, bio-ecology, agronomy/agro-ecology and pesticide screening. By mapping those monetary streams against a country’s in-house capacity and their model IPM programme structure, rewarding opportunities could be identified for bolstered funding, inter-country cooperation or technical backstopping (Figure 9).

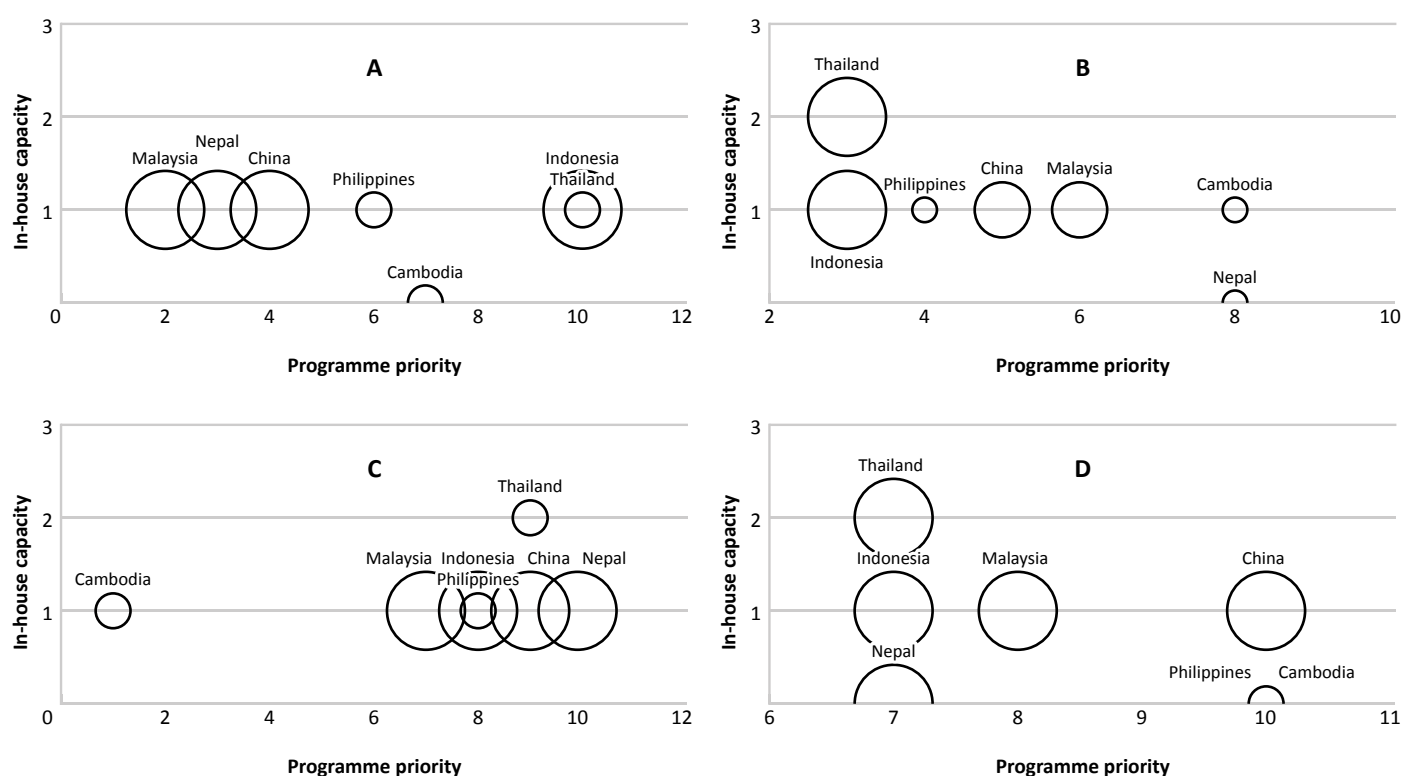


Figure 9. Comparative mapping of domestic scientific capacity, programmatic priority and funding status for four key crop protection domains in seven Asia-Pacific countries. Plots are drawn for pest/disease biology and ecology (A), biological control (B), agronomy and agro-ecology (C) and varietal resistance (D). For each domain and country, bubble size refers to the current funding status. In all graphs, except for B, the largest bubble size refers to intermediate funding while the smallest bubbles indicate lacking funds. Programmatic priorities refer to countries' envisioned model IPM framework and are ranked from 0 to 10 (see Figure 5), while in-house capacity is plotted on a 0 to 2 scale.

For the domain of pest/disease bio-ecology (Figure 9-A), several countries did recognize its status as a foundational IPM component but were constrained by low capacity and funding. While this domain received a 10/10 ranking by Thailand, insufficient domestic capacity and lack of funds prevented this country from fully tapping its potential. Agronomy and agro-ecology underpin cultural control (Figure 9-C) – a core IPM component, as recognized by six out of seven countries. Only Thailand held robust domestic capacity (but absent funds) to effectively wield this domain within IPM programmes. The domain of biological control received priority attention from Cambodia and Nepal (Figure 9-B). Yet, both nations lacked finances and adequate in-house capacity to deploy it for pest management. Conversely, Indonesia and Thailand did possess major scientific capacity, but downplayed the importance of biological control within IPM. Lastly, for the domain of varietal resistance (Figure 9-D), viable funding streams were in place for all countries except Cambodia and the Philippines. These two countries, plus Nepal, also lacked sufficient capacity on this crucial IPM avoidance tactic.

No graphs were generated for the domains of pest/disease diagnostics and pesticide efficacy screening, for which there either was adequate regional capacity or an overall low prioritization in countries' model IPM programmes (see Figures 5 and 8).

Based upon this mapping exercise, future development assistance can be delivered in a tailored and (potentially) more effective fashion. As such, for each of six scientific domains, opportunities are pinpointed for strengthened regional collaboration, external technical backstopping, bolstered financial support and/or first-hand assistance with IPM programme re-design (Table 3). China, Malaysia and Thailand possess solid in-country capacity in one or more domains; their close engagement and (eventual) leadership within regional IPM programmes can thus prove rewarding. In the meantime, considering how very

few nations possess solid domestic capacity in certain domains (e.g. pest bio-ecology, agro-ecology), external technical backstopping continues to be a must. Possibly, this can be achieved by engaging IPM scientists from North America, Europe or Oceania in an accompanying role. This modus operandi is also proposed for biological control, as the Asia-Pacific countries with baseline in-house capacity downplay its importance within IPM schemes. Lastly, in terms of funding priorities, financial support for pesticide (both chemical and biological) screening can be facilitated, preferably, through the private sector.

Domain	Country						
	Philippines	Cambodia	Malaysia	China	Thailand	Nepal	Indonesia
Diagnostics and epidemiology	C _r	C _r , F	-	C _p	C _p , F	C _r , F	C _r
Bio-ecology	T, F	T, F	T, R	T	T	R	T
Agronomy and agro-ecology	F	F, R	-	-	C _p , F	-	-
Biological control	C _r , T, F	C _r , T, F	-	-	C _p , R	C _r , T, F	R
Varietal resistance	C _r , F	C _r , F	-	-	C _p	C _r	-
Pesticide efficacy	F	R, F	C _p	-	C _p	C _r , R, F	-

Table 3. Mapping of tactical interventions in sustainable crop protection for seven Asia-Pacific countries. Interventions are outlined for six scientific domains, with diagnostics and epidemiology lumping two underlying domains with insufficient data. For agronomy and agro-ecology, the associated IPM programmatic component is cultural control and sanitation. Based upon Figure 9, the following interventions are proposed: regional collaboration (C), external technical backstopping (T), bolstered funding (F) or assistance with programme re-design (R). Those countries that have the potential to assume a leadership-role in regional initiatives are highlighted in grey.

a. On regional collaboration, subscripts 'p' and 'r' refer to countries being a respective provider or receiver of Asia-level support.

In terms of target commodities, crop protection research within most Asia-Pacific countries covered a broad range of food crops, for example, rice, maize, vegetables and perennial fruits. In Viet Nam, rice, vegetables and fruit crops received a respective 40 percent, 30 percent and 20 percent of scientific attention. Similar commodity foci were adopted in China and Malaysia, although export

crops such as oil-palm received 30 percent of the research attention in Malaysia. Conversely, 10 percent of the scientific attention went to devising IPM programmes for tea in China. In terms of neglected crops, survey respondents indicate a need to pay more attention to vegetables, rice, corn and a range of food crops such as buckwheat, soybean, perennial fruits and finger millet.

Policy and legislation

Among the surveyed Asia-Pacific countries, 67 percent have a national IPM policy. As core constituents of an IPM programme, decision criteria such as action thresholds or economic thresholds (ET) ideally should feature prominently within such policy. These criteria provide crop-, pest- and locality-specific information on the injury level at which a curative intervention (e.g. biopesticide spray application) is warranted and economically justified. Locally validated thresholds are of critical importance to farmers and agri-food producers, as they help rationalize pest management, avoid superfluous pesticide expenditures and minimize its negative environmental

impacts. Unexpectedly, China and Thailand are the only countries where more than two ETs have been incorporated into the national IPM policy (Table 4). So far, ETs have only been defined for a very small complement of animal pests or pathogens of cereals and annual horticultural crops such as cabbage, tomato, watermelon and potato. Several major agricultural producers (Nepal, the Philippines and Viet Nam) do not consider ETs or other related decision criteria, thus creating fertile ground for rampant pesticide misuse or over-use (e.g. Schreinemachers *et al.*, 2020).

Table 4. Listing of arthropod pests and plant pathogens for which ETs have been defined, validated and communicated in different Asia-Pacific countries. Certain names of individual countries are abbreviated. For Indonesia and Malaysia, ETs are specified per crop instead of target pest/pathogen.

Pest/disease taxon	Country								
	Philippines	Cambodia	Viet Nam	Malaysia	China	Thailand	Nepal	Indonesia	Singapore
<i>Bemisia tabaci</i>	-	-	-	-	-	X	-	-	-
<i>Chilo suppressalis</i>	-	-	-	? ^a	X	X	-	?	-
<i>Cnaphalocrocis medinalis</i>	-	-	-	-	X	-	-	-	-
<i>Liriomyza brassicae</i>	-	-	-	-	-	X	-	-	-
<i>Locusta migratoria</i>	-	-	-	-	X	-	-	-	-
<i>Loxostege sticticalis</i>	-	-	-	-	X	-	-	-	-
<i>Mythimna separata</i>	-	-	-	-	X	-	-	-	-
<i>Nephotettix virescens</i>	-	-	-	?	-	X	-	?	-
<i>Nilaparvata lugens</i>	-	X	-	?	X	X	-	?	-
<i>Plutella xylostella</i>	-	X	-	-	-	-	-	-	-
<i>Sitobion miscanthi</i>	-	-	-	-	X	-	-	-	-
<i>Sogatella furcifera</i>	-	-	-	?	X	-	-	?	-
<i>Thrips palmi</i>	-	-	-	-	-	X	-	-	-
Plant pathogens									
<i>Fusarium graminearum</i>	-	-	-	-	X	-	-	-	-
<i>Magnaporthe oryzae</i>	-	-	-	?	X	-	-	?	-
<i>Phytophthora infestans</i>	-	-	-	-	X	-	-	-	-
<i>Puccinia striiformis</i>	-	-	-	-	X	-	-	-	-
<i>Rice black-streaked dwarf virus</i>	-	-	-	?	X	-	-	?	-

a. Lack of sufficient data on the exact crop x pest focus.

The efficacy, accessibility and consistent performance of pesticides have led to their wide-scale use among agri-food producers in the Asia-Pacific region. The AIs of pesticides are continuously being registered, with Asian countries annually registering 3.3 ± 1.5 new AIs. The registration pace is highest in China, where on average four to eight AIs are being registered for in-country use. Except for China, most Asia-Pacific countries do not seem to have a robust, comprehensive pesticide risk assessment programme. Among the nine surveyed countries, only five routinely evaluate the efficacy, phytotoxicity and residues of candidate AIs on target agricultural crops under laboratory and/or field conditions. Many countries appear to use legislation from industrialized countries as a proxy for pesticide safety (Galt, 2008), and remain far from running their own full-fledged multi-criteria risk assessments. Cambodia, China and Viet Nam reportedly screen the ecological selectivity of new pesticide AIs towards beneficial organisms that occur in local agro-ecosystems. Yet only respondents from China elaborated on the number, type and identity of beneficial organisms that are included in those risk assessment assays. Strengthening countries' pesticide risk assessment programmes can enable the selection of both effective and environmentally selective AIs and/or usage modes, thus minimizing conflicts with biological control and pollination services (e.g. Amarasekare *et al.*, 2016; Egan *et al.*, 2021). Considering the fast pace of AI registration among Asia-Pacific countries and the ineptness of (most) prevailing registration procedures, this likely could become a priority intervention.

In recent years, numerous crop pests have acquired resistance to a broad range of pesticidal modes of action (MoA) and the preservation of susceptible organisms for effective chemical control has become an overpowering global challenge (Jørgensen *et al.*, 2018; Mota-Sanchez and Wise, 2021). To preserve the utility of these synthetic compounds, insecticide resistance management (IRM) has been promoted since the 1980s by all major agro-chemical companies. Biological control agents and biopesticides have also just been included in the MoA classification and associated IRM schemes (Sparks *et al.*, 2020). To avoid the continuing emergence of insecticide resistance, six Asia-Pacific countries recommend rotating AIs with different MoAs; eight (out of nine) countries further assert that biological control (e.g. biopesticides) is indeed formally included in national IRM plans. Yet, so far, only a few biological control agents are commercially available in the above countries. While Viet Nam and Malaysia cannot name any registered biological control products, two other countries only refer to an in-country availability of *Bacillus thuringiensis* (Bt) endotoxins. Cambodia, Indonesia and Thailand complement Bt preparations with

one or two entomo-pathogenic fungi (e.g. *Metarhizium anisopliae*, *Beauveria bassiana*, *Trichoderma harzianum*) and/or nucleo-polyhedrosis viruses (NPV). Nepal makes six different biopesticides (species-level) commercially available to its farmers, while China deploys an arsenal of tens of different species, strains and commercial formulations.

In order to further promote the uptake of biological control, respondents lay out several different policy options. China, Nepal and Singapore indicate how a relaxation of (or exemption from) registration requirements should be considered for certain biological control products and semio-chemicals, for example, pheromones for mating disruption. For invasive pests, the registration process of such products can potentially be fast-tracked through a so-called green channel. China equally underlines the need to strictly monitor and enforce the quality of (imported, locally produced) biological control agents. Guidelines and protocols are readily available for quality testing in North America and Europe (e.g. Gaugler *et al.*, 2000; van Lenteren *et al.*, 2003), and these possibly can be adapted to the Asian farming context. Cambodia and the Philippines identify soft policy interventions, hinting at options to incentivize farmer behaviour by subsidizing biological control or by adopting premium pricing for organic (or pesticide-free) produce.



4. Taking the pulse of countries' fall armyworm mitigation programmes

Current invasion status and management response

At present, FAW has been recorded in South Asia, Southeast Asia and Northeast Asia. Also, incursions have been reported in different parts of the Pacific, such as in New Caledonia, Papua New Guinea and Timor-Lest (EPPO, 2021). Yet, there is a critical dearth of reliable, on-the-ground data on its country-level prevalence, in-field incidence, yield loss and management costs (Table 5). When drawing upon surveys that were run over 2020/2021, there are no accurate distribution or impact figures for most countries. At the country-level, FAW appears to cover between 0.1 percent (the Philippines) and 80 percent of the maize-growing areas and attains field-level incidence up to 80 percent. In most countries (except for China; Wang *et al.*, 2020), economic impacts are largely confined to maize though foliar feeding is reported in crops such as sorghum, sugarcane or forages.

While FAW-induced yield losses in Cambodia are believed to attain 50–80 percent, its perceived impacts are modest in other countries. Similarly, current management costs range between USD 40 (Nepal) and USD 500 (Indonesia) per hectare and year. Despite large inter-country variability, these figures possibly reflect reality. Aside from being shaped by field-level incidence, crop phenology and foliar damage (e.g. Toepfer *et al.*, 2021; Overton *et al.*, 2021), monetary impacts of FAW are modulated by local market dynamics (i.e. supply and demand), availability and pricing of crop protection inputs, or agro-ecological conditions. Considering how the latter comprise meteorological factors (i.e. rainfall frequency, temperature), plant nutrition and the degree of soil degradation, the impacts of FAW are likely magnified in certain drought-afflicted or degraded agro-ecosystems such as Cambodia, Thailand and Viet Nam. Along the same lines, pest-related losses can be deepened where natural pest control services have been progressively weakened due to intensified agricultural production and heavy pesticide use such as in Viet Nam's river deltas, China's Yangtze basin or Cambodia's Tonle Sap floodplains (Tang *et al.*, 2021).

Table 5. Key features of the FAW invasion in Asia-Pacific countries. Per country, information is provided on the main affected crops and FAW prevalence (percentage of area affected), field-level incidence (percentage of plants affected), yield loss (percentage of lower productivity) and estimated management costs in maize. The latter captures the additional financial expenditure for pest control in USD per hectare and year. Data are drawn from a 2021 online survey and from email-based questionnaires sent out by TEF at different times during 2020.

a. M: maize; Ca: cabbage; Su: sugarcane; So: sorghum; R: rice; V: vegetables; W: wheat

Country	Affected crops	Prevalence (%)	Incidence (%)	Yield loss (%)	Management costs
Bangladesh	M, Ca ^a	-	5-60	-	-
Bhutan	M	-	-	-	-
Cambodia	M	80	80	50-80	-
China	- ^b	-	-	-	+USD 195 ^c
Indonesia	M	2	80	-	+USD 500
India	M, So	-	-	-	-
Myanmar	M	-	-	2-5	-
Nepal	M, So	39	16.5	6.4	+USD 40
Democratic People's Republic of Korea	M, So, R, V, W	40	-	-	-
Papua New Guinea	M, So, Su, R	-	-	-	-
Philippines	M, Su, So	0.1	0.6	2	-
Sri Lanka	M, So, V	-	10-30	1-5	-
Thailand	M	10-15	-	25-40	-
Viet Nam	M	4.5	-	5-40	-

b. No data

c. Yang *et al.*, 2021.

For invasive pests such as FAW, a country's management response is likely shaped by available resources, the

magnitude of actual field-level impacts (including in the published literature), and how those compare with losses due to readily established pests. Out of the four surveyed countries, Cambodia and Nepal anticipated that FAW-related impacts would surpass those of readily established organisms (Figure 10). In the Philippines however, FAW was expected to pose less of a threat in terms of yield losses and social-environmental impacts.

Asia-Pacific countries currently find themselves at different stages in devising and implementing their

FAW mitigation programmes. Respondents ranked the overall maturity and inclusiveness of their countries' FAW mitigation programme between 50 and 70 on a scale from 0 to 100 (100 being solid and mature). In terms of notable features of those mitigation programmes (including scientific advances or innovations), three countries highlighted the launch of (pheromone-based) monitoring and field scouting operations. The in-country identification and mass-production of biological control agents was considered a major advance by Nepal and the Philippines. Lastly, Indonesia emphasized how government-supported efforts bolster the capacities of both farmers and extension workers.

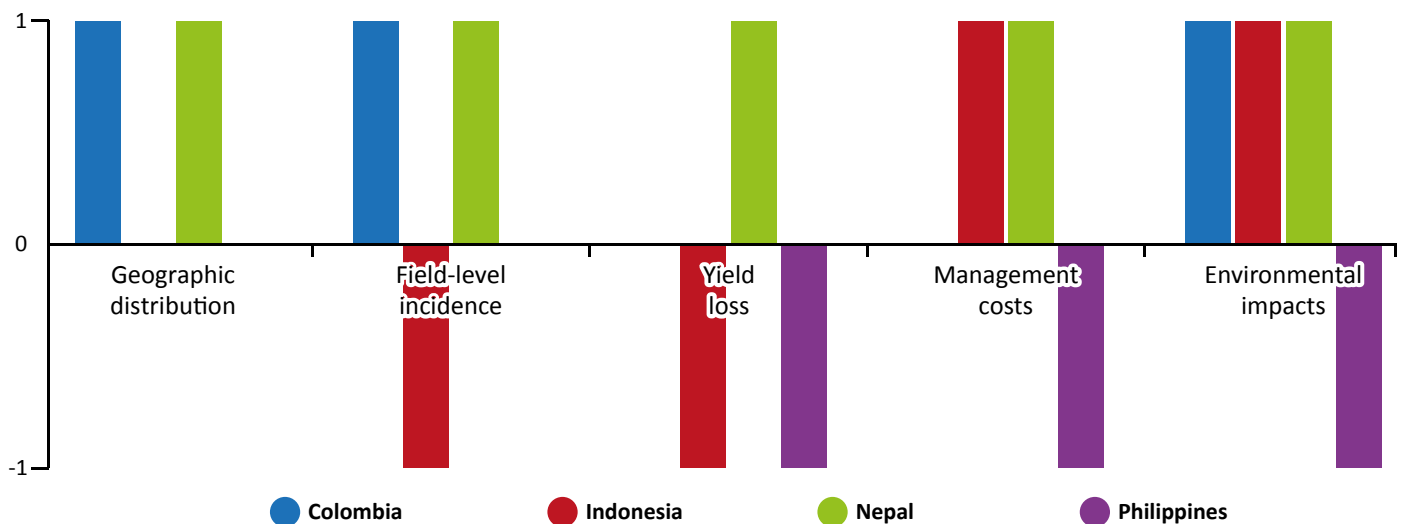


Figure 10. Perceived importance of FAW as compared with already established (i.e. endemic, invasive) pests. FAW is either deemed to pose a higher (1), similar (0) or lower (-1) hazard to the agriculture sector of four priority countries. Pest-related hazards are assessed for five core characteristics.

Individual countries laid out different strategic directions within their FAW mitigation programmes (Figure 11). Cambodia and the Philippines prioritized activities such as FAW taxonomy and strain delineation, basic ecology and biology, and the systematic tracking of its geographical spread. While Nepal and Indonesia placed far greater emphasis on the development, validation and transfer of management approaches. Surprisingly, none of the four

countries paid much attention to reviewing the global FAW literature. Also, the assessment and economic valuation of FAW-induced losses was assigned low to intermediate levels of importance. Yet, in order to devise effective management programmes, it is essential to gauge judiciously the economic impacts of newly invasive pests such as FAW (Overton *et al.*, 2021).

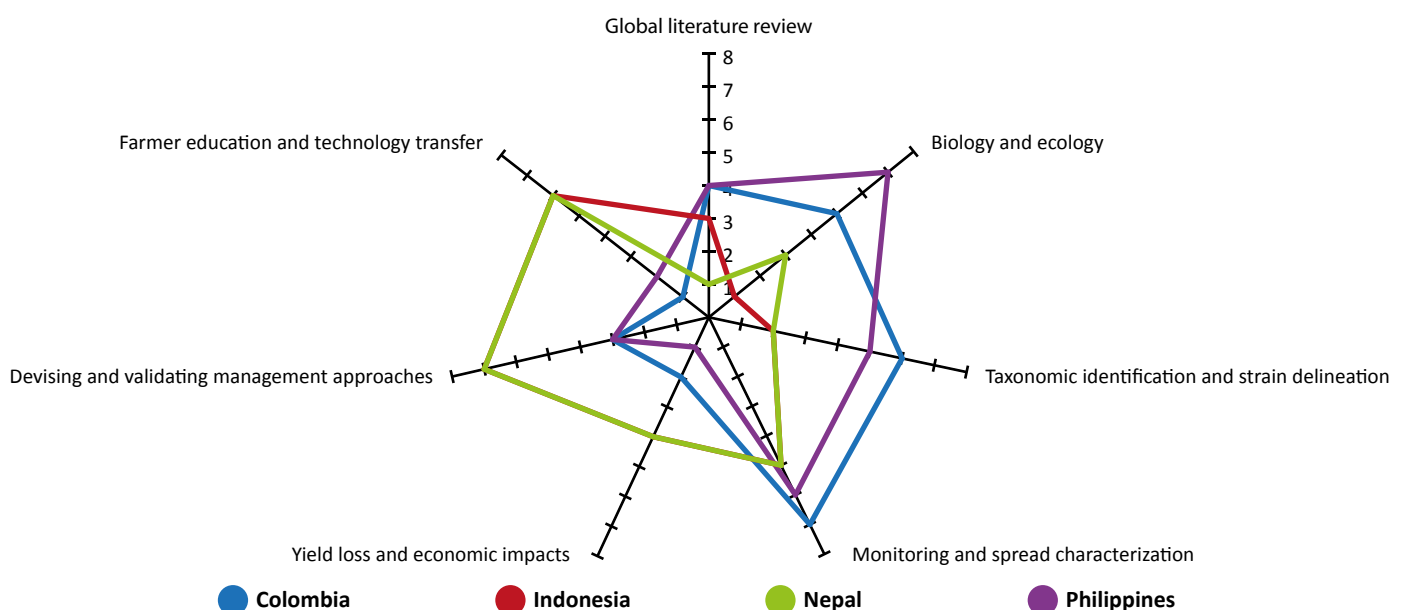


Figure 11. Relative ranking of seven core components within the FAW mitigation programme of four Asia-Pacific countries. The radar plot reflects the relative importance ascribed to each of seven activities, with higher scores assigned to comparatively more important activities.

Pest identity, biology and ecology

A timely, accurate identification of pest invaders is a core component of surveillance efforts, mitigation programmes and IPM packages. Furthermore, by gaining an in-depth appreciation of the pest's biology and ecology, one can anticipate its infestation pressure and seasonal dynamics, delimit its geographical distribution, and devise effective management practices. Since the 2019 arrival of FAW, four Asia-Pacific countries have mainly focused on 1)

characterizing its life cycle, 2) assessing feeding damage on different maize phenological stages, and 3) discovering associated natural enemies in the prevailing agro-ecologies (Figure 12). So far, lesser degrees of attention have been paid to unveiling FAW host strain or insecticide resistance profiles, delineating its (plant) host range or quantifying climatic impacts on pest development (e.g. under laboratory conditions).

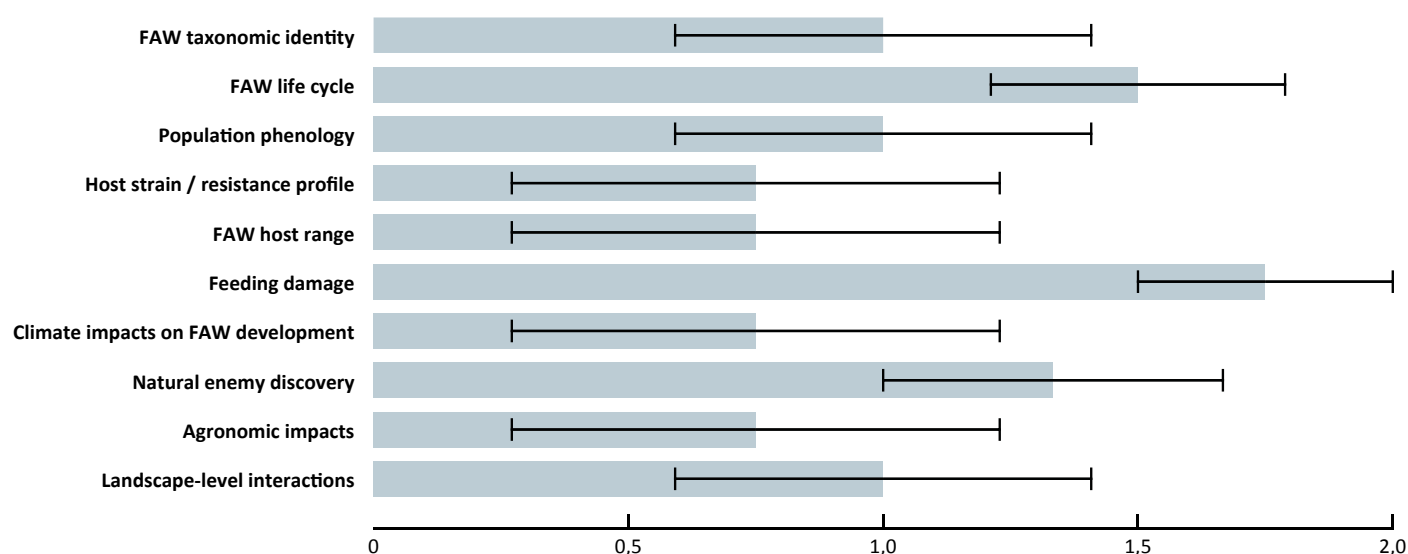


Figure 12. Current emphasis on key facets of FAW identity, biology and ecology in Cambodia, Indonesia, Nepal and the Philippines. For each scientific domain, progress is assessed on a scale from 0 to 2 (2 being major advances) and average values (\pm SE) are calculated across all four countries.

When crafting FAW mitigation programmes, individual countries set out priorities that may (or may not) be aligned with their domestic scientific capabilities (Figure 13). As such, priority domains for which in-country capacity is lacking constitute lucrative targets for development assistance and/or inter-country collaboration. Concerning FAW identity, biology and ecology, three or more countries identified deficient national capacity related to host range elucidation (I5), climate-related development (I7) and agronomic effects on pest populations (I9). Conversely, zero countries identified insufficient capacity in domains related to the characterization of the FAW life cycle (I2) or the description of its feeding damage on maize (I6). Most countries defined their programme emphases in line with those domestic capabilities. As such, countries omitted several key domains from their national IPM programme

with Nepal only concentrating on five (out of ten) scientific domains, for example. On the other hand, some countries did prioritize certain domains despite a lack of basic in-country expertise, thus being subject to concrete capacity gaps. In the Philippines, major gaps were identified in all domains except for life cycle characterization (I2), host strain or resistance profile classification (I4) and the description of FAW feeding damage (I6). These gaps in seven priority domains potentially constrain IPM programme development. In Cambodia, one minor gap related to the quantification of climate-dependent development (I7). Despite lacking capacity in several scientific domains, only Indonesia petitioned to receive international support regarding the characterization of landscape-level interactions (I10).

There was limited awareness regarding FAW resistance to pesticidal compounds, with Cambodia and Nepal expressing no concern that FAW might be resistant to pesticides. Given the incidence of field-evolved resistance

in invasive FAW populations and the actual presence of pyrethroid-resistant strains in Indonesia (Zhang *et al.*, 2019; Gui *et al.*, 2020; Boaventura *et al.*, 2020), this misconception urgently needs to be fixed.

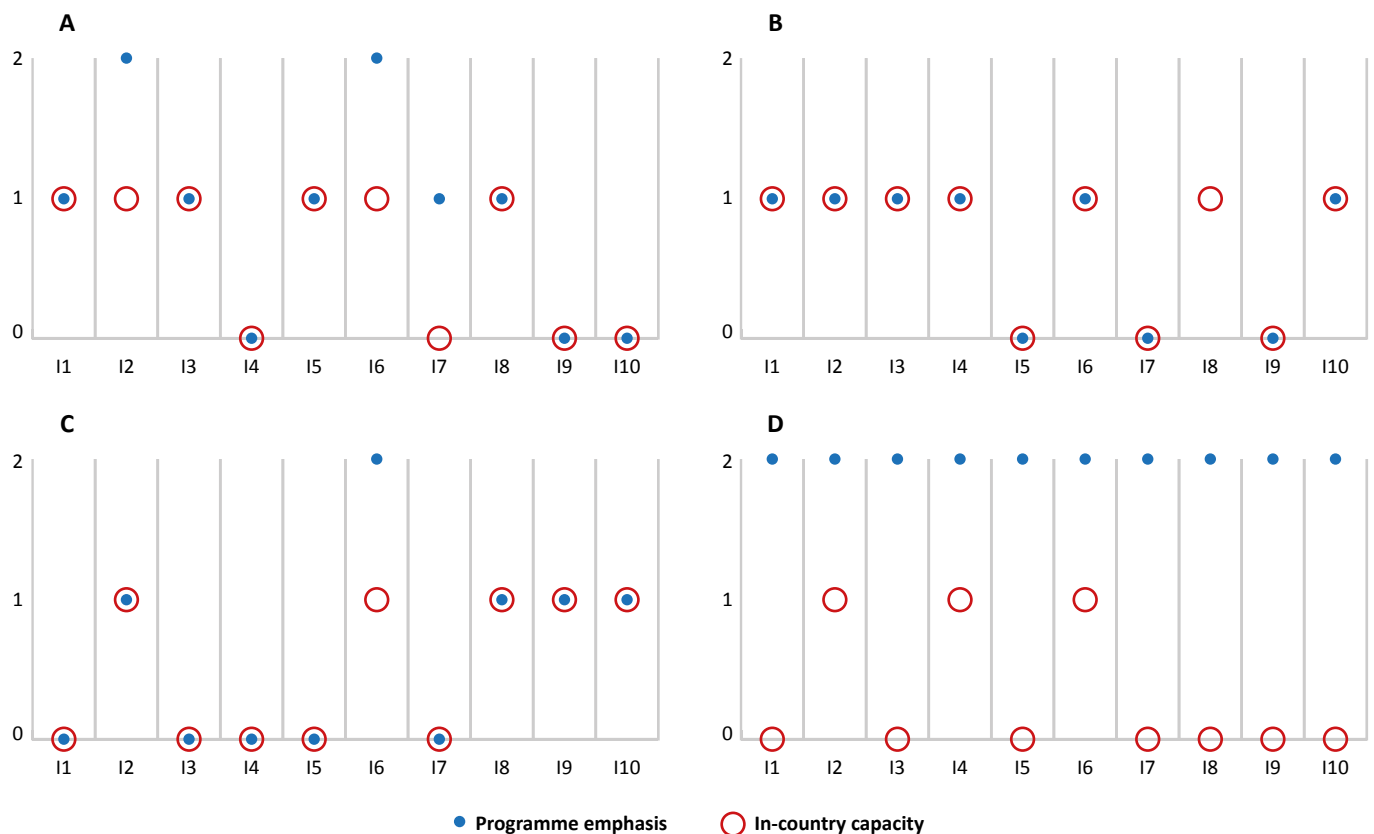


Figure 13. Country-level alignment of national scientific capacity with programmatic priorities regarding FAW identity, biology and ecology. In-country capacities and programmatic priorities are either ranked from 0 to 1 (1 being solid capacity) or from 0 to 2 (2 being major emphasis), respectively. Patterns are shown for Cambodia (A), Indonesia (B), Nepal (C) and the Philippines (D). Gaps are visualized for ten different scientific domains, with the respective alphanumeric codes explained in Appendix III.

FAW ecology proved to be a popular research topic, with ample attention dedicated to the discovery and description of natural enemies associated with FAW field populations. All countries provided extensive details on the identity of local natural enemies, listing multiple species of egg or larval parasitoids, predators (e.g. ants, lacewings,

stinkbugs and predacious beetles), entomopathogenic fungi, baculo-viruses and nematodes. However, it remains to be seen whether countries will progress beyond this initial stage of biodiversity description towards harnessing its power for sustainable pest control (Gonzalez-Chang *et al.*, 2020; see section III).

Monitoring and field scouting

Phytosanitary surveillance is a process of methodical information gathering on certain pests or diseases within a given area, and comprises detection schemes, delimiting surveys or field-level monitoring. Likewise, crop scouting activities can be undertaken by farmers and plant protection officers alike in order to gauge infestation pressure, evaluate economic risks and define eventual needs for curative control. Monitoring and field-level scouting thus constitute central components of a national IPM programme. Upon arrival of a new pest such as FAW,

the necessary surveillance procedures need to be defined, validated and communicated. At present, the four Asia-Pacific countries have made sound progress in crafting an FAW surveillance toolbox (Figure 14), concentrating on 1) formulating scouting protocols, and 2) training extension officers and plant protection personnel. Only scant attention has been paid to topics such as pest forecasting, evaluating different bait or light traps, and exploring the potential use of remote sensing, drones or insect radar.

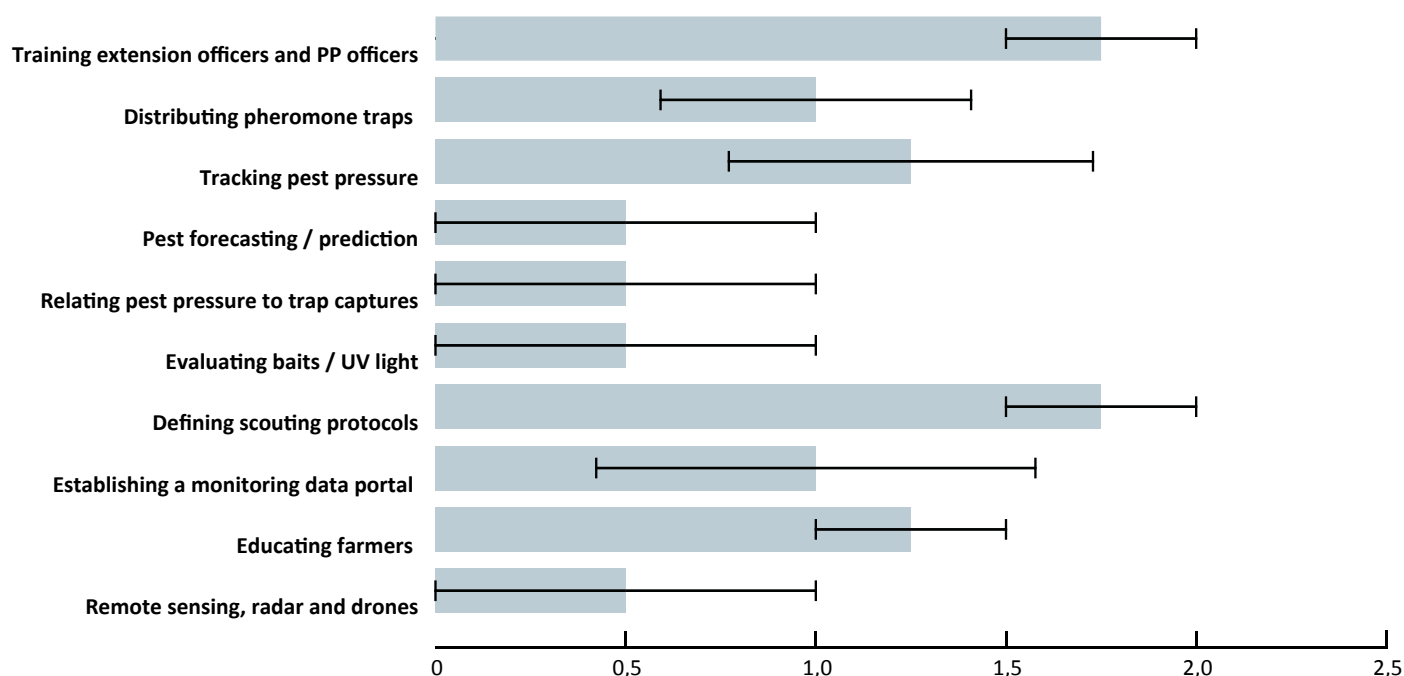


Figure 14. Current emphasis on key facets of FAW surveillance and field-level scouting among four Asia-Pacific countries (Cambodia, Indonesia, Nepal, the Philippines). For each domain, progress is assessed on a scale from 0 to 2 (2 being major advances) and average values (\pm SE) are calculated across all four countries. PP refers to plant protection.

So far, the FAW surveillance programme of all four Asia-Pacific countries was found to be incomplete and unbalanced (Figure 15). Overall, five to six core domains proved to be absent in countries' surveillance programmes – except for the Philippines, where all ten domains were emphasized. This piecemeal approach to FAW surveillance plausibly relates to countries' deficient domestic capacities in this field. Specifically, individual countries signaled a critical lack of capacity in five to eight surveillance domains. These include key activities such as establishing a centralized data portal (M8), forecasting seasonal pest pressure (M4) or selecting bait traps for monitoring purposes (M6). As a result, the few domains in which a given country had even rudimentary (scientific)

capabilities featured in its surveillance programme. Yet, some countries did prioritize certain domains in the absence of critical capacity – thus experiencing concrete capacity gaps. Indonesia faced a major capacity gap to systematically track FAW infestation pressure over space and time (M3). In the Philippines, major capacity gaps were noted in all domains except for training a cadre of plant health professionals or extension personnel (M1), and for establishing a centralized monitoring platform or early-warning system (M8). Lastly, Cambodia encountered a minor capacity gap to train plant health professionals (M1) and to distribute pheromone traps among FAW-affected farmers (M2).

In order to upgrade their FAW surveillance programme, individual countries requested international support in the following domains: pest modelling and forecasting (Indonesia), furnishing FAW traps and lures (Nepal), pheromone testing and remote sensing (the Philippines). At present, FAW monitoring data have not been related to biophysical or meteorological parameters (e.g. rainfall, temperature, altitude, soil type) in any of the four countries. The latter, however, could be a rewarding area for international collaboration.

Lastly, despite the immature status of countries' surveillance programmes, systematic FAW monitoring is reportedly carried out across 3–50 percent of maize cropping areas nationally while 4–20 percent of a country's farmers reportedly deploy traps in their fields. Traps are routinely used for control purposes; they can also become a valuable decision-support tool once FAW trap-capture data have been formally linked with in-field pest pressure and action thresholds (e.g. Short *et al.*, 2017).

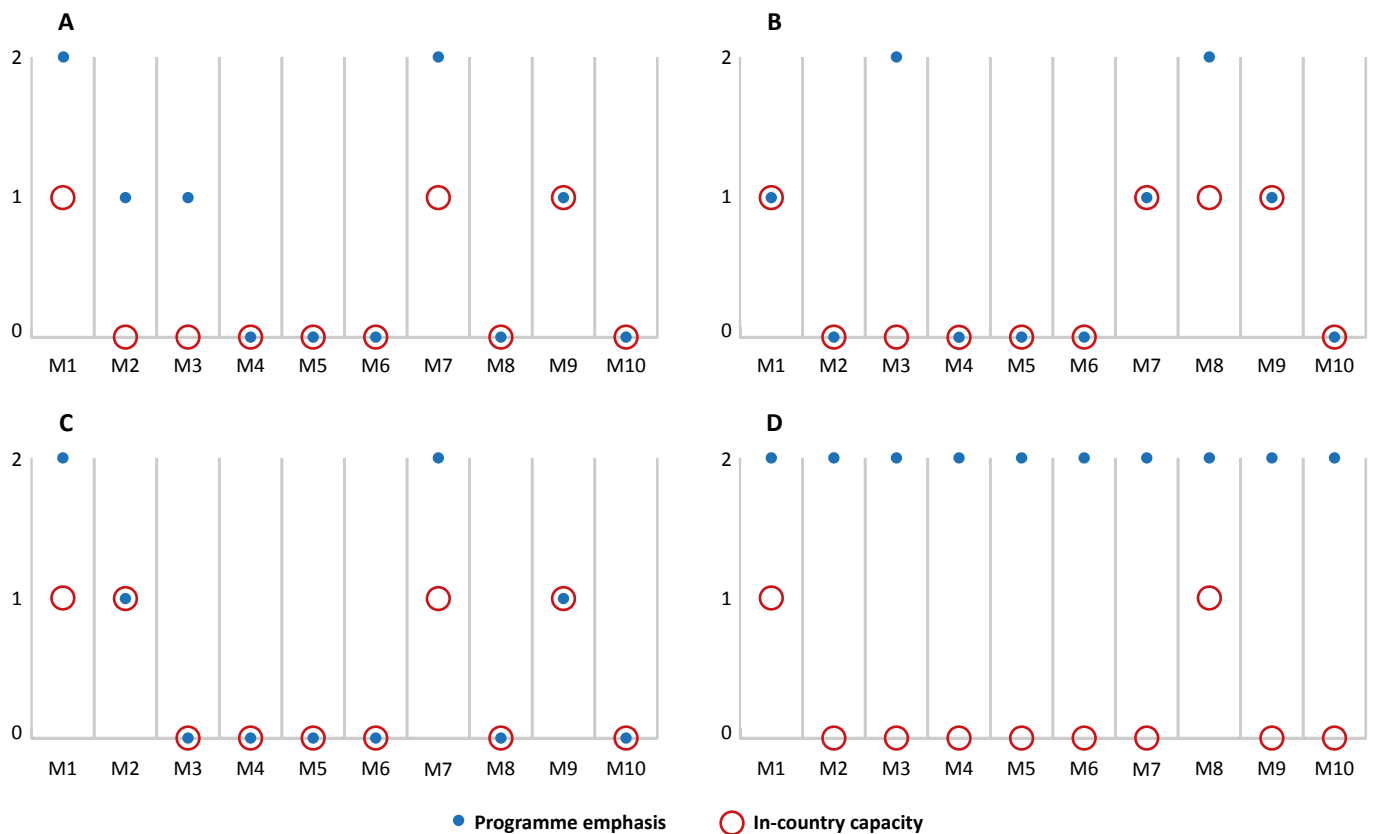


Figure 15. Country-level alignment of national capacity with programmatic priorities regarding FAW monitoring and field-level scouting. In-country capacities and programmatic priorities are either ranked from 0 to 1 (1 being solid capacity) or from 0 to 2 (2 being major emphasis), respectively. Patterns are shown for Cambodia (A), Indonesia (B), Nepal (C) and the Philippines (D). Gaps are visualized for ten different domains, with the respective alphanumeric codes explained in Appendix III.

Fall armyworm prevention and control

Following the FAW invasion of Africa, many nations favoured a pesticide-centered mitigation approach and endorsed the unguided application of chemical insecticides (Day *et al.*, 2017). Consequently, vast numbers of African farmers have since embraced pesticides for FAW control (Kumela *et al.*, 2019). On the other hand, Asian nations such as China and India strengthened their IPM programmes by incorporating biopesticides, intercropping and egg parasitoids. Also, considering how many Asian senior crop protection officers graduated from FAO's 1990s FFS programme, they might be inclined to pursue the full repertoire of IPM tools without diluting its core principles. Yet, relative to other thematic fields, the four Asia-Pacific countries have only made scant progress in outlining the curative or preventative control components within their FAW mitigation programmes (Figure 16). While none of the countries reported major advances in any of ten key scientific domains, all signaled having made some progress in evaluating biopesticides. Least progress was made in 1) selecting FAW-resistant or tolerant maize varieties, 2) validating habitat or landscape management tactics, and 3) employing FAW semio-chemicals for mating disruption. Cambodia and the Philippines laid out full-fledged FAW mitigation programmes that touched upon seven to eight key scientific domains.

Aside from being shaped by available resources and the relative importance of FAW (in comparison with other pests and diseases), the immature status of a country's prevention and control programme relates to its domestic capabilities (Figure 17). All countries confirmed possessing a baseline capacity to screen biopesticides (C8), while three countries also held in-house expertise to evaluate cultural control measures (C2) or to assess the efficacy of synthetic pesticides (C5). Some countries bore insufficient capacity on multiple fronts. For example, Nepal and the Philippines could only draw on the necessary expertise in three (out of ten) domains. Yet, domestic capacity only defined programmatic emphases to a certain degree. Despite possessing credible capacity in all ten scientific domains, Indonesia downgraded the following domains in its FAW mitigation programme: screening varietal resistance (C1), evaluating cultural or mechanical control measures (C2, C9), validating habitat/landscape management tactics (C4), and using semio-chemicals for mating disruption (C6). On the other hand, certain countries did prioritize domains for which they possessed no in-country expertise – thus facing concrete capacity gaps. Cambodia and the Philippines faced a capacity gap to evaluate mechanical control. In addition, the Philippines faced minor gaps in four other domains: screening resistant varieties (C1), examining cultural control tactics (C2), deploying semio-chemicals for mating disruption (C6) and establishing spray thresholds (C7).

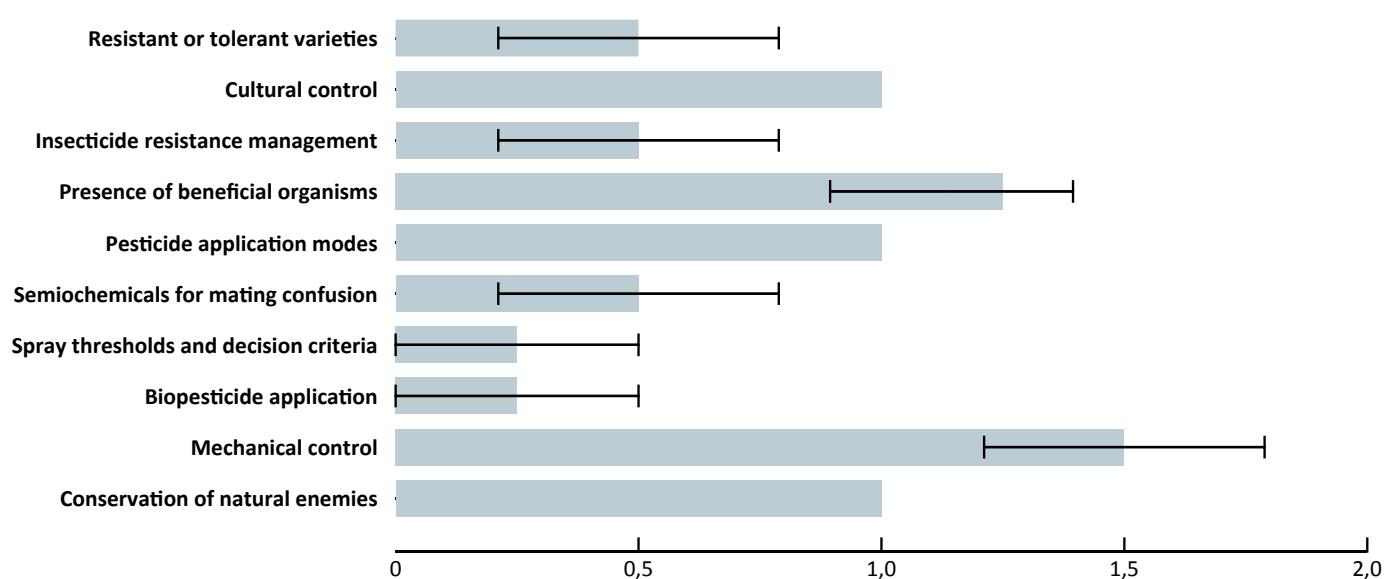


Figure 16. Current emphasis on key facets of FAW prevention and control among four Asia-Pacific countries (Cambodia, Indonesia, Nepal, the Philippines). For each domain, progress is assessed on a scale from 0 to 2 (2 being major advances) and average values (\pm SE) are calculated across all four countries.

Except for Cambodia, all countries solicited international support related to FAW prevention and control. Assistance was requested in the following domains: habitat and landscape management, IRM, varietal resistance screening, natural enemy ecology, semiochemical-based crop protection, push-pull technology and biological control.

Ultimately, the maturity and inclusiveness of a country's FAW mitigation programme will be mirrored in farmers' management responses. When asked to rank eight management practices in terms of their popularity among local farmers, chemical and manual control were invariably placed near the top (position 4.8 ± 0.8 ,

with 8 being most popular). Establishing intercrops also proved popular (position 4.5 ± 1.2), but farmers were thought to refrain from releasing natural enemies (2.3 ± 1.3) or doing nothing (1.3 ± 0.8). Similarly, respondents thought that pesticide usage rates had increased by 25–60 percent in maize since the 2019 arrival of FAW, with Indonesian maize growers currently making up to five spray applications per season. This reflects the risk-averse behaviour that many resource-poor smallholders exhibit when facing invasive pests (Upadhyay *et al.*, 2020). Under those conditions, farmers easily revert to insecticide sprays despite insufficiently trustworthy information on their efficacy (Kumela *et al.*, 2019).

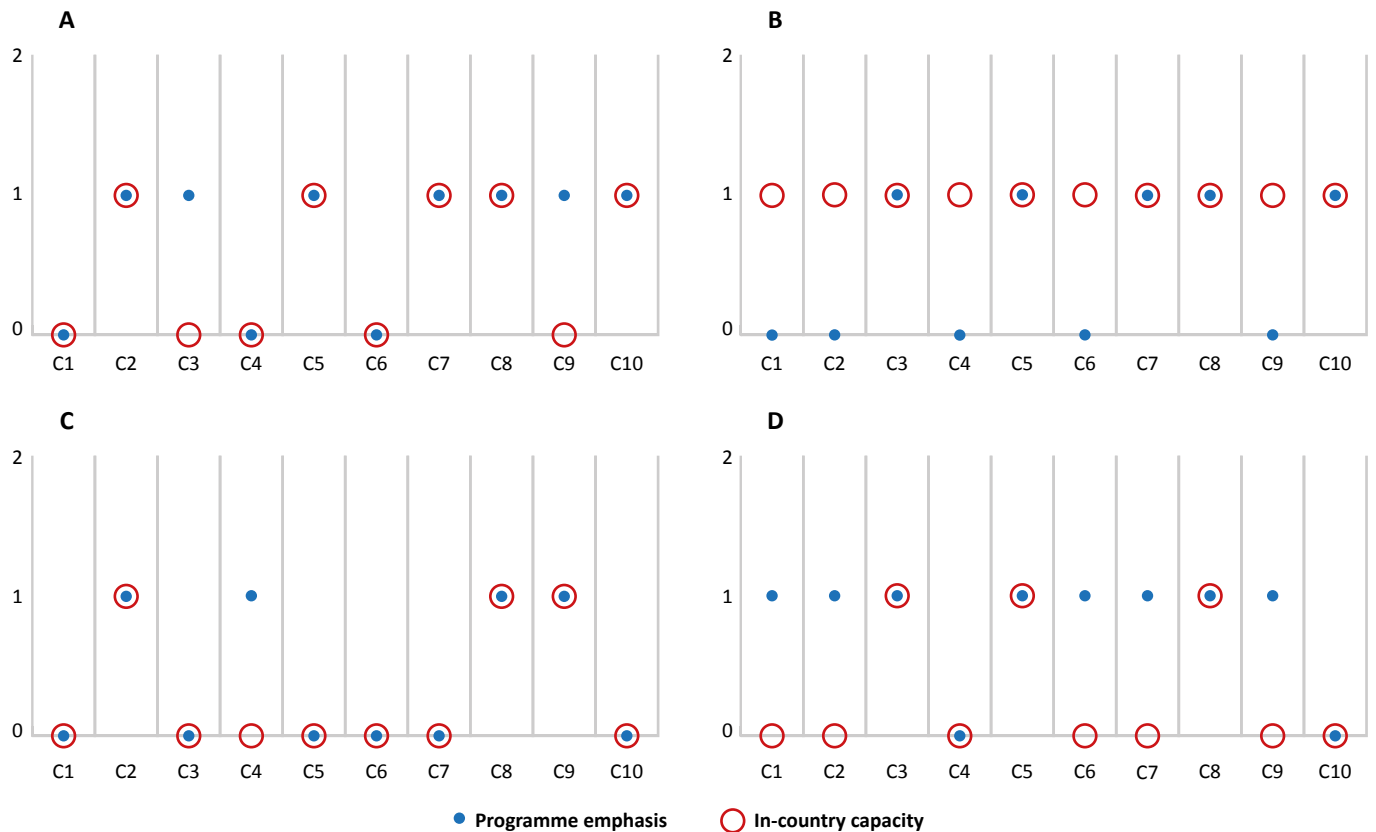


Figure 17. Country-level alignment of national scientific capacity with programmatic priorities regarding FAW prevention and control. In-country capacities and programmatic priorities are either ranked from 0 to 1 (1 being solid capacity) or from 0 to 2 (2 being major emphasis), respectively. Patterns are shown for Cambodia (A), Indonesia (B), Nepal (C) and the Philippines (D). Gaps are visualized for ten different scientific domains, with the respective alphanumeric codes explained in Appendix III.

Though all four Asia-Pacific countries actively screen biopesticides and study the ecology of FAW's natural enemies (Figure 16), biological control has not (yet) found a firm foothold among farmers. Indeed, despite the flourishing basic and applied research, its actual in-field adoption is routinely constrained by multiple hurdles (Barratt *et al.*, 2018; Wyckhuys *et al.*, 2018). As a result, biological control research often does not yield concrete social-ecological outcomes.

Drawing upon a new spiral approach (Gonzalez-Chang *et al.*, 2020), we map the extent to which countries have progressed along a six-step sequence departing from the concept of biodiversity (i.e. in-field discovery of natural enemies) towards harnessing its power for sustainable FAW control (Figure 18). Given that FAW invaded Asia as recently as 2019, we are entirely conscious that biological control science has not yet come full circle. First, most advances have so far been made in describing FAW-associated natural enemies in local farm settings and in elucidating their life history aspects (e.g. longevity,

fecundity). Second, the population ecology of key biological control agents remains critically understudied. Third, biological control information is already being transmitted to local maize growers, for example, through FFS. Fourth, initial progress is being made in mobilizing biodiversity for pest control, for example, by devising natural enemy rearing/release protocols or by evaluating habitat management tactics. In the developing-world tropics, it is not uncommon to see the latter ecosystem service providing protocols being formulated without even rudimentary insights into pest or natural enemy ecology (Wyckhuys *et al.*, 2020b). Hence, it is of the utmost importance to 1) tread with caution, and 2) ensure that those recommendations that ultimately reach growers are efficacious and underpinned by solid science. By doing so, one raises the odds that early adopters confirm the validity of biological control innovations and do not stifle their broader diffusion among farmer peers (Catalini and Tucker, 2017; Wyckhuys *et al.*, 2018). Moving along lightly can mean outright failure, especially when faced with low-cost, accessible chemical alternatives.

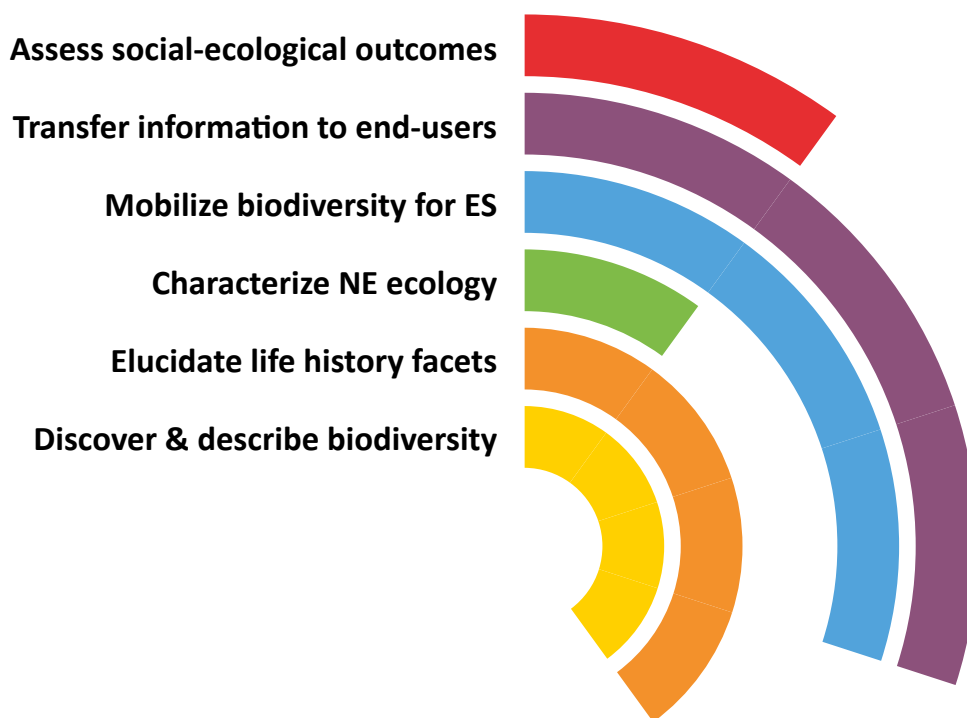


Figure 18. Schematic visualization of the progress of FAW biological control science along a six-step, outcome-oriented impact pathway for four Asia-Pacific countries. Within the concentric donut chart, the exact circumference of each loop mirrors the relative amount of attention to a given theme (as indicated by survey respondents). Themes depart from the measurement of farm-level biodiversity (inner-most circle) to culminate in the envisioned social-ecological outcomes. ES: ecosystem services; NE: natural enemy.

Regarding the different biological control organisms, the four Asia-Pacific countries reportedly dedicated most attention to FAW parasitoids (ranking 5 out of 8). This was followed by microbial agents (viruses, fungi and bacteria ranking 4/8) and invertebrate predators (ranking 3/8). Respondents enumerated a myriad of arthropod natural enemies such as *Telenomus* spp. or *Trichogramma* spp. egg parasitoids as (potentially) effective FAW biological control agents. Conversely, nematodes and vertebrate predators (e.g. insectivorous birds, rats, rodents, frogs) received no scientific attention in any of the four countries.

Among the three main forms of biological control, most scientific attention was paid to conservation biological control (ranking 4/8). This form of biological control seeks to manage (invasive) pests by supporting the in-field populations of naturally occurring beneficial organisms, such as insect predators or parasitoids (Barbosa, 1998; Landis *et al.*, 2000). This can be achieved by providing key dietary resources (e.g. floral nectar, alternative prey), deliberately avoiding disturbances (e.g. pesticide applications) and establishing shelter habitat. Given that conservation biological control seeks to mobilize resident biodiversity for pest control, countries' emphasis is fully justified as part of a short-term or immediate management response.

On the other hand, all four Asia-Pacific countries totally disregarded classical biological control (ranking 0/8). This form of biological control entails the scientifically guided release of (host-specific) exotic organisms from the pest's region of origin and constitutes a tailor-made solution for the long-term suppression of invasive pests (e.g. Wyckhuys *et al.*, 2020b). Over the past century, this form of biological control has permanently resolved problems with at least 43 insect pests across the Asia-Pacific region. Considering how multiple natural enemies act against FAW in the Americas, this practice potentially can bring long-term relief. Yet, its implementation is obstructed by a lack of public awareness, unwieldy regulatory environments and a risk-averse attitude (Heimpel and Cock, 2018). Hence, adequate messaging and stakeholder education are essential to ensure that classical biological control is not being ignored, and that it features prominently within a long-term FAW mitigation plan.

Farmer extension and participatory research

Over the past decades, farmer extension programmes have evolved from early paternalistic, top-down technology-transfer initiatives to full-fledged bottom-up, participatory schemes such as FAO's FFS. For invasive pests, these extension programmes need to be well-designed and preferably couple the transfer of locally relevant IPM technologies with tailored education to fill in the most pressing farmer knowledge gaps. When asked to rank the extent of farmers' knowledge on different topics, respondents from the four Asia-Pacific countries felt that local farmers were most familiar with mechanical

control (Figure 19). Rather surprisingly, farmers were also thought to possess a basic-to-good understanding of (the identity and ecological role of) natural enemies in farm plots. On the other hand, farmers were unfamiliar with a diverse set of topics such as IPM decision criteria and biopesticide application methods. Hence, despite the ample scientific attention given to biopesticides and sequential IPM decision-making schemes (e.g. Figures 2, 5, 16), it is unlikely that Asian farmers will properly deploy them against FAW.

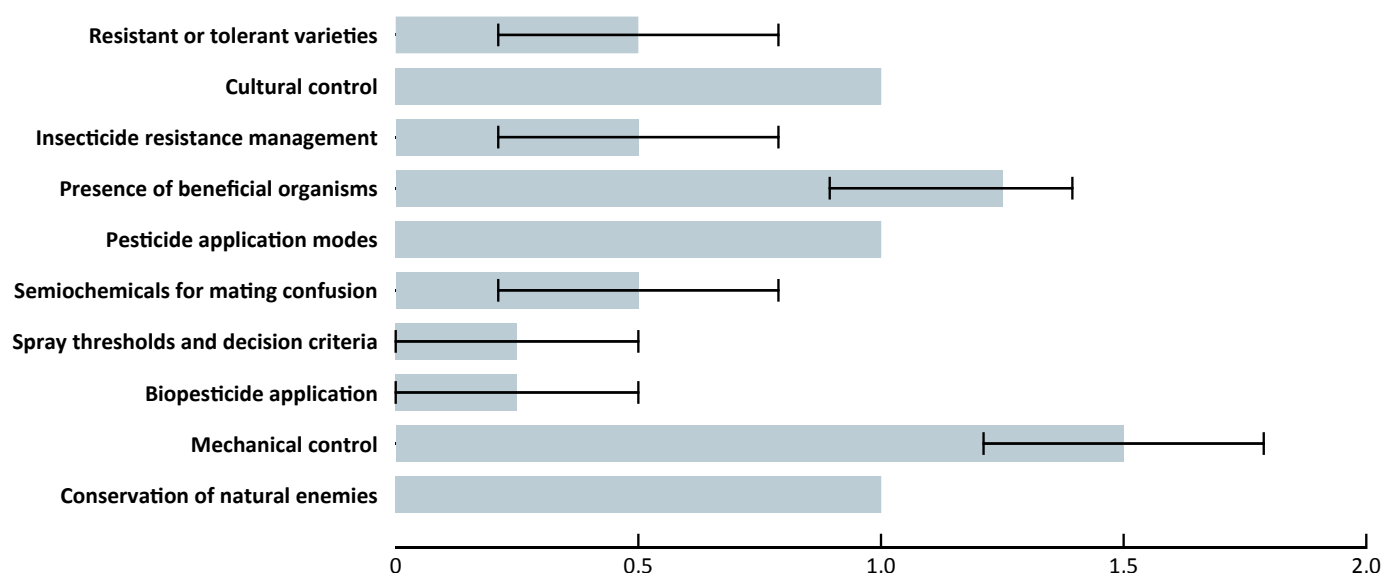


Figure 19. Comparative extent of farmers' understanding of ten different pest management domains in four Asia-Pacific countries (Cambodia, Indonesia, Nepal, the Philippines). For each domain, the extent of farmer knowledge is assessed on a scale from 0 to 2 (2 being sound understanding) and average values (\pm SE) are calculated across all four countries.

Farmers' knowledge, attitudes and practices are profoundly shaped by real-world experiences and farm-level observations (Wyckhuys *et al.*, 2019), but can also be influenced to some extent by well-designed education programmes. Among the four countries, FAW extension programmes proved to be relatively complete and covered at least six (out of ten) priority domains (Figure 20). While Cambodia's extension programme was reportedly all-inclusive, other countries faced critical gaps. Three countries indicated how IPM spray thresholds and decision criteria (E7) were not addressed; inadequate attention was also paid to FAW-tolerant or resistant varieties (E1) and IRM (E3). In those countries, favourable conditions are thus created for pesticide abuse and the associated development of insecticide resistance. All countries, however, gave adequate coverage of cultural or mechanical control (E2, 9), natural enemy identity (E4), biopesticide application (E8) and conservation biological

control (E10). Based upon the exact layout of their extension programmes, individual countries can steer farmers' management actions: Cambodia, Indonesia and Nepal are well-equipped to correct the lack of knowledge among farmers on biopesticide use (E8). Other countries, however, experience clear extension gaps; for example, Nepal's current extension programme is ill-suited to train farmers on varietal resistance (E1), IRM (E3), semiochemical use (E6) or spray thresholds (E7). Across all four countries, these extension gaps are most pronounced for promoting IPM decision criteria and spray thresholds (E7). Hence, in order to bolster the farm-level uptake of IPM, countries' extension programmes and underlying research initiatives clearly need to be overhauled (Figures 2 and 5). Extension programmes can also be broadened by including participatory research and farmer-scientist co-innovation. The latter themes were recognized as extremely important by all countries except for Cambodia.

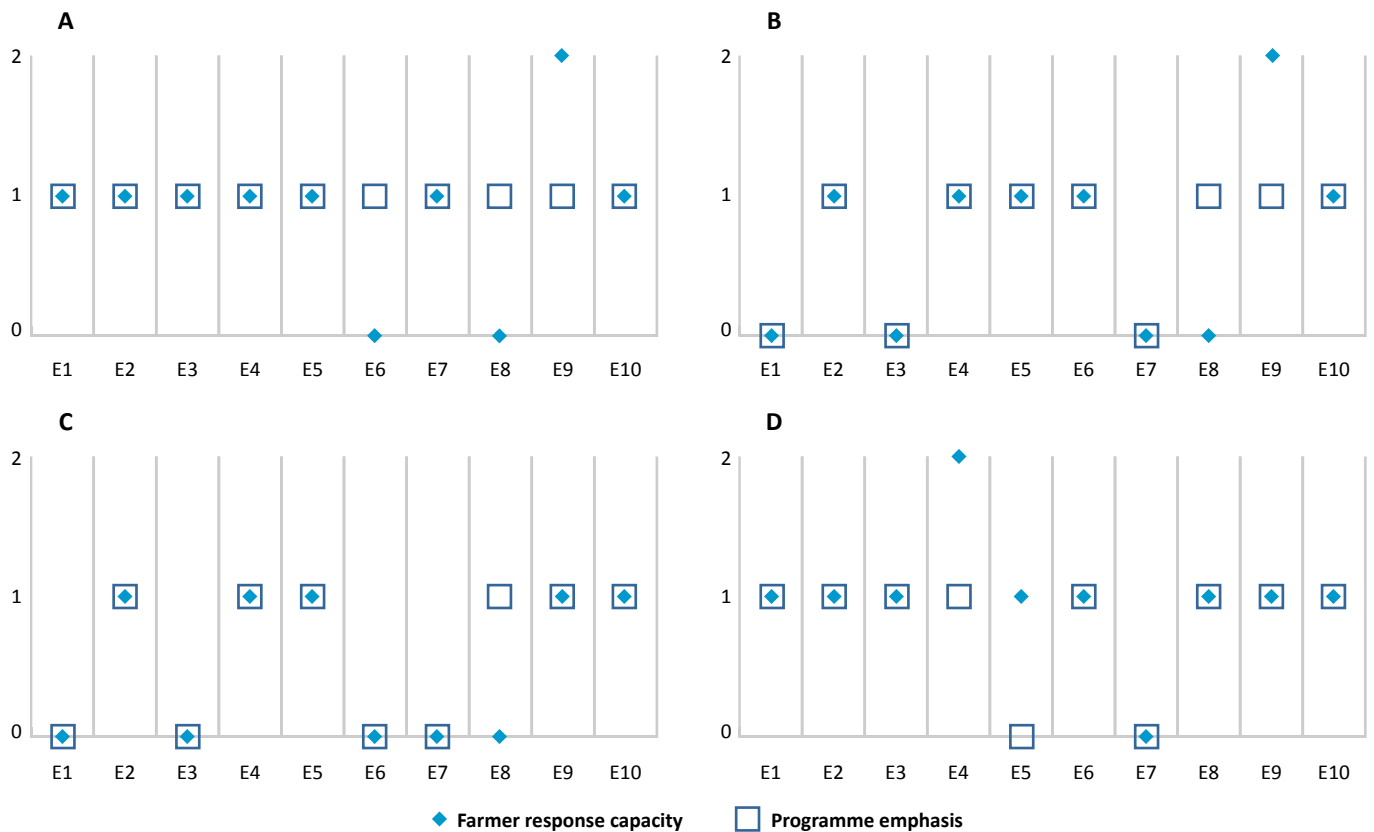


Figure 20. Country-level alignment of farmers' response capacity with the actual make-up of extension programmes. Farmers' response capacities and programmatic emphases are either ranked from 0 to 2 (2 being major emphasis) or from 0 to 1 (1 being solid capacity), respectively. Patterns are shown for Cambodia (A), Indonesia (B), Nepal (C) and Philippines (D). Gaps are visualized for ten different extension domains, with the respective alphanumeric codes explained in Appendix III.

Individual countries differed greatly in their appreciation of the way farmers manage FAW. Indonesia and Nepal considered their actual management to be highly deficient (25–30 on a scale from 0 to 100, with 100 being very good). Equally, Cambodia and the Philippines considered their local farmers to be coping relatively well and ranked current management practices as high as 70–77. Three out of four countries underlined a need to bolster farmer awareness of biological control (including biopesticides), while individual countries also signaled training needs on FAW bio-ecology, varietal resistance, effective non-chemical control, field-level scouting and seed treatments. Drawing on experiences from FAO's FFS programme, both

Cambodia and Indonesia signaled that field-level training and observation-based learning are critical components of a FAW extension programme. Conversely, Nepal indicated that farmers could potentially improve the way they manage FAW by strengthening the supply chain for plant protection products (i.e. synthetic pesticides and non-chemical inputs). Indeed, by involving the private sector in up-scaling, FAW IPM could be most rewarding, as the number of crop protection salesmen and industry-funded crop advisors are believed to outnumber formal government extension personnel by 3 to 1 (the Philippines) and 10 to 1 (Nepal).

Policy and regulation

Some of the main hurdles to overcome when implementing IPM and invasive pest management pertain to the inadequate policies and (unwieldy) regulatory environments at national and international levels (Nghiem *et al.*, 2013; Barratt *et al.*, 2018; Bakker *et al.*, 2020). These policies either directly impede the development of IPM technologies, prevent an in-country registration of non-chemical alternatives or obstruct their farm-level uptake and diffusion. Among the four Asia-Pacific countries, the latter pathway is recognized as a key obstacle for the sustainable management of FAW. Three countries believe that the reach and impact of FAW mitigation programmes can be greatly improved through enhanced attention to farmer training, for example with FFS.

Since the 2018/19 invasion of FAW, 14 synthetic compounds and 1 botanical insecticide have been locally registered for use against this pest (Table 6). Out of these compounds, 40 percent pose high risks to human or environmental health (Jepson *et al.*, 2020). Among the four countries, chlorantraniliprole, emamectin benzoate and lambda-cyhalothrin are the most popular – with the latter two compounds posing very high risks to pollinators, fish and aquatic invertebrates. Despite being listed as the most toxic compound for pollinators, spinosad 45 percent suspension concentrate (SC) is one of four recommended formulations in Nepal. It is concerning, however, that countries do not fully disclose all registered compounds and that farmers revert to cheaper, toxic alternatives. For example, Kandel and Pudel (2020) signal how methomyl, methyl parathion, chlorpyrifos and malathion are regularly applied against FAW in Nepal. These include highly hazardous organo-phosphates for which usage is banned either globally or locally.

To create the necessary momentum for IPM and to avoid unnecessary risks to human and environmental health, all countries can consider revisiting their list of recommended products and prioritize low-risk compounds. Along the same lines, countries tend to follow a piecemeal approach in assessing pesticide-related risks. For new compounds, product performance is assessed by three (out of four) countries and hazards for non-target organisms are reportedly evaluated by two countries. Other aspects such as post-application exposure, pesticide spray drift, human health hazards or environmental fate receive little or no attention. Yet, concrete opportunities exist for individual countries to amend existing policies or selection criteria and thus ensure that FAW control does not compromise “One Health” (Damalas and Eleftherohorinos, 2011; Wyckhuys *et al.*, 2020a).

Among invasive FAW populations in Africa and Asia, resistance has been recorded for multiple active ingredients (Zhang *et al.*, 2019; Boaventura *et al.*, 2020; Gui *et al.*, 2020). Three countries elaborated on their IRM strategy for FAW. All the countries recognized how an over-reliance upon synthetic pesticides can trigger insecticide resistance development and rapidly derail sustainable pest control (Jørgenson *et al.*, 2018). Two countries reportedly expanded their IRM by incorporating biopesticides or botanicals. Yet, so far, those intentions are not mirrored in an increased availability of the latter products or in an alleviation of existing registration barriers for non-chemical alternatives. At present, only *Bacillus thuringiensis* (Bt) crystal proteins are commercially available in three countries and fungal preparations of *Beauveria bassiana* are marketed in Nepal. In the Philippines, farmers also have access to one botanical insecticide i.e. Neem oil. The set of available biopesticides urgently needs to be expanded and diversified, especially in light of the fast-paced registration (or label expansion) for synthetic pesticides.

Table 6. List of pesticide active ingredients (AI) and botanical compounds that have been registered for use against FAW within the four Asia-Pacific countries. For each AI, efficacy against the target pest (i.e. FAW) and risks to human and environmental health are enumerated (based upon Jepson et al., 2020). For high-risk compounds, specific "One Health" risks are indicated and their respective ranking among the ten most toxic pesticides is given. The most popular AIs are highlighted in grey.

Compound	Number of countries	Efficacy	"One Health" risk	Elevated risk
Abamectin	1	Poor to fair	High	-
Azadirachtin ^a	1	Good to excellent	Low	-
Chlorpenafyr	1	- ^b	-	-
Chlorantraniliprole	3	Good to excellent	Low	-
Chlorfluazuron	1	-	-	-
Cyantraniliprole	1	-	-	-
Emamectin benzoate	4	Good to excellent	High	Pollinator (2)
Flubendiamide	1	Good to excellent	Low	-
Indoxacarb	1	Good to excellent	High	-
Lambda cyhalothrin	3	Good to excellent	High	Fish (5); aquatic invertebrate (8)
Pyridalyl	1	Unknown	High	-
Spinetoram	2	Good to excellent	Low	-
Spinosad	1	Good to excellent	Low	Pollinator (1)
Tetraniliprole	1	-	-	-
Thiamethoxam	1	Poor to fair	High	Pollinator (5)

^a Botanical insecticide; ^b No data

Across the globe, biopesticides and invertebrate natural enemies are either produced in large-scale mass-rearing facilities or in small-scale units (so-called cottage industry; van Lenteren *et al.*, 2018). The former facilities are occasionally set up with contributions from the private sector, for example Brazilian sugarcane growers, Mexican cattle farmers, Colombian coffee producers or the Thai cassava industry. Indonesia and the Philippines confirm that government support is equally given to similar kinds of units in both their countries, including material supplies, access to facilities, equipment or technical training.

On the other hand, community IPM centres in Nepal culture micro-organisms such as *Trichoderma harzianum* (see also Khadka and Uphoff, 2019). It is advisable to build upon those experiences to up-scale the production of different micro- and macrobials for FAW management.

Lastly, national policies also need to be re-directed in order to favour certain non-chemical IPM tools and technologies. Here, the different Asia-Pacific countries specifically recommend inclusion of 1) varietal resistance screening, and 2) community-level, participatory action research that addresses non-chemical controls for FAW.



5. Conclusions and lessons learned

Animal pests and plant pathogens constrain global agri-food production, compromising food security, human nutrition and societal wellbeing. Often propagated at an inter- and intra-continental scale, several of these biotic threats constitute TPPs. At present, invasive TPPs cause over USD 150 billion/year losses to Asian agriculture while endemic pests attain outbreaks of ever-increasing magnitude. IPM and its underlying agro-ecological components represent a desirable, tailor-made solution to alleviate those TPP impacts. Yet, its farm-level uptake and Asia-wide diffusion is facing several prominent hurdles.

During early 2021, two online surveys were launched to systematically review current Asia-Pacific plant protection programmes. Despite low survey response rates, this diagnostic assessment shone light on the actual make-up, maturity and inclusiveness of national IPM programmes. First-hand insights were also gained into countries' response capacity and mitigation plans in the face of recent invasions by FAW.

Countries targeted 23 distinct pathogens and 55 animal herbivores, prioritizing rice blast and bacterial blight, Panama disease, Tephritid fruit flies, brown planthopper, diamondback moth, beet armyworm and FAW. Priority pests afflicted multiple food and livelihood security crops, such as rice, corn, vegetables and perennial fruits. TPP-induced crop losses were deemed to be worth up to USD 5 000 per hectare/year. Overall, phytosanitary programmes were well-aligned with the IPM pyramid conceptual model, though its foundational components (e.g. decision criteria, pest bio-ecology, biological control) are regularly overlooked.

Asia-Pacific farmers lag in adopting field scouting, decision-support tools and trapping, while unguided pesticide use has become the mainstay of farmers' pest management. This proliferation of chemical control is habitually ascribed to stakeholders' deficient knowledge, inadequate policies and (supposed) immature IPM technologies. Survey respondents signal how farmers need to be better equipped to apply agro-ecological tactics and underscore a need for (participatory) experiential learning. Pesticide over-use is perceived as a pressing concern in Cambodia, Indonesia and Malaysia; these countries could be fertile grounds for re-invigorated IPM campaigns.

Core plant protection staff recognize the importance of IPM avoidance measures and decision-support tools. Hence, external forces likely obstruct their due inclusion in actual phytosanitary programmes. Overall, countries deemed it entirely feasible to cut pesticide use by 37.5 percent (up to 100 percent) nationwide, with amended smart farming techniques being an immediate, cost-effective way to alleviate TPP problems. Biological control is a prime IPM alternative that delivers multiple win-win social-environmental outcomes; yet, four (out of five) of its perceived technology attributes hamper its diffusion. Specifically, biological control is felt to be less compatible, observable or trialable, and more complex than pesticidal approaches.

Though plant health science receives slightly less attention and funding than other fields, Asia-Pacific countries have acquired robust in-house capabilities in diagnostics, pesticide efficacy screening and socioeconomics. Domestic capacities and countries' conceptual understanding of IPM are used to pinpoint rewarding opportunities for bolstered funding, inter-country cooperation and specialized technical backstopping. Within regional initiatives, China, Malaysia and Thailand potentially could assume a lead role in advancing certain IPM programme components.

Though many Asia-Pacific nations possess an IPM policy, decision-support tools receive little attention and the approach to pesticide risk assessment (and the ensuing product registration) is piecemeal. Countries annually register an average of 3.3 pesticide AIs, but only China appears to consistently screen their (non-target) impacts on beneficial organisms. Though farmers' use of biopesticides can avoid insecticide resistance development and thus extend the lifespan of certain AIs, there is limited in-country availability of effective, practical non-chemical tools. Both soft and hard policy options, including command-and-control measures, are put forward to restrain pesticide use and enhance access to biological control alternatives.

Since 2018, FAW has made its appearance in the Asia-Pacific. Despite a critical dearth of on-the-ground data, FAW prevalence, incidence and (perceived) impact vary greatly between and within countries. Yet, among four countries, its anticipated impacts exceed those of readily established (endemic, invasive) organisms. Countries find themselves at different stages of rolling out their FAW mitigation programmes and follow a myriad of strategic directions. Some FAW-afflicted nations prioritize the development, validation and transfer of pest management technologies, while others proceed outlining its taxonomy, basic ecology and spatial distribution.

Regarding pest identity, biology and ecology, most progress has been made in describing the FAW life cycle, assessing its feeding damage and discovering associated natural enemies. Overall, countries advanced their programmatic activities in line with their domestic scientific capabilities. Capacity gaps were commonly recorded in characterizing the FAW host range or climate-related development, and in capturing the effects of agronomic parameters. These gaps constitute suitable targets for future development assistance. Plant protection staff also need to be educated on the existence of field-evolved insecticide resistance among FAW populations.

At present, FAW surveillance programmes are fragmented and unbalanced; systematic monitoring is reportedly carried out across 3–50 percent of national maize cropping areas using a multitude of trapping tools, damage assessments and physical surveys. Tangible progress has been made in formulating scouting protocols and in training a cadre of plant protection officers. Yet, scant attention has been paid to pest forecasting, evaluating traps or bait substrates, implementing FAO's FAW Monitoring and Early-Warning System (FAMEWS) application, and screening the potential use of drone- or radar-technologies. Individual countries signaled a critical lack of capacity in 6–8 (out of 10) surveillance domains, requesting support in epidemiological modelling, pheromone testing or remote sensing.

Countries have made the least progress in defining curative or preventative control options for FAW, with most advances reportedly made in evaluating biopesticides. Within their FAW mitigation programme, several countries have downgraded domains for which they bear insufficient capacity, for example in assessing cultural control measures or screening varietal resistance. As a result, farmers have come to favour chemical or manual control of FAW; insecticide usage rates in Asia's maize crop have reportedly increased by 25–60 percent over the past two years.

Despite vibrant research on FAW egg parasitoids and entomo-pathogens, biological control has not yet found a firm foothold among Asia's maize growers. Drawing upon an interactive, spiral approach, we visualize how countries have made scant progress towards truly harnessing the power of agro-biodiversity for sustainable FAW control. While recommendations are already being transmitted to end-users (farmers), key insights into the population ecology of FAW and its natural enemies are often still lacking. Hence, to secure the uptake of biological control by early adopters, it is crucial to tread with caution, adopt a sequential approach and scientifically underpin early-stage innovations.

Asian farmers are thought to be the least familiar with IPM decision criteria, resistance management schemes and biopesticide application modes. Yet, so far, three (out of four) countries do not tackle the former two themes while also disregarding FAW-resistant varieties. Farmers' management behaviour can be improved through refurbished extension programmes in which ample attention is given to participatory research, observation-based learning and farmer-scientist co-innovation.

Inadequate policies and unwieldy regulations feature among the core obstacles that thwart the diffusion of IPM and biological control. At present, countries' legislative environments decidedly favour pesticidal approaches and obstruct the swift registration of non-chemical alternatives. Since 2019, 14 chemical compounds (40 percent high-risk AIs) and one single botanical insecticide have been registered for FAW. As for biopesticides, only *Bacillus thuringiensis* (Bt) and *Beauveria bassiana* are available for use in a few countries. Considering how governments regularly provide support (monetary, technical, infrastructure) for natural enemy mass-rearing, the prospects for upgrading facilities and accelerating the mass-production of both micro- and macrobials for FAW control are bright.

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Appendix I

Survey 1 - Eagle-eye view on Asia-Pacific crop protection

Section I – Starter

- Q1.** On what country are you reporting?
- Q2.** What pests / diseases are covered in your country's pest management programme? Provide a full listing of Latin and/or common names of target pests / diseases. Example: fall armyworm (*Spodoptera frugiperda*), *Nephotettix virescens*, etc.
- Q3.** What pests / diseases receive priority in your country's pest management programme? Indicate Latin name of the pest / disease and afflicted crop. Example: *Spodoptera exigua* in tomato.
- Q4a.** What direct impacts do crop pests / diseases cause in your country? Provide a rough estimate of the economic magnitude of pest-induced yield losses (USD per hectare and year).
- Q4b.** Provide a rough estimate of the indirect financial losses (costs for pest control) incurred by farmers (approximate figure in USD per hectare and year). How much money do farmers in your country spend for crop protection on an annual basis, per hectare?
- Q4c.** Pests and diseases can negatively impact farmer livelihoods and slow rural development. Rank the importance of these socio-economic impacts in your country, on a scale from 1 to 100 (1 being unimportant to 100 being very important).
- Q5.** List the key features of your country's national pest management programme. Freely list any components, starting with the most important one.
- Q6a.** Are you familiar with the concept of integrated pest management (IPM)? Yes/no
- Q6b.** How much attention is paid to the following IPM components within your country's national pest management programme (from 0 being unimportant to 100 being very important)?
1. Resistant or tolerant crop varieties
 2. Crop sanitation and cultural control, e.g. planting date / spacing / crop arrangements
 3. Pesticide resistance management
 4. Pest / disease sampling protocols
 5. Habitat / landscape management
 6. Efficacious pesticides
 7. Spray thresholds and decision criteria
 8. Biopesticides / biological control agents
 9. Mechanical and physical control, e.g. tillage, soil solarization, weeding, trapping
 10. Baseline insights into pest biology / ecology

Section II – Management behaviour of farmers

- Q7a.** At present, what crop protection tools / techniques do your country's farmers use? Freely list any management approaches, starting with the most common tactic.
- Q7b.** Do your country's farmers adopt IPM? Why / why not?
- Q8.** When interpreting the degree of IPM adoption / diffusion, the following seven hurdles are often identified. Each hurdle prevents IPM adoption in its own unique manner. In your country, evaluate the relative importance of each hurdle (from 1 to 10, with 1 being relatively unimportant and 10 being very important).
1. Knowledge (e.g. insufficient knowledge of farmers / technicians, limited research on local pests / farming systems)
 2. User preferences (e.g. farmer / stakeholder attitudes towards pests, pest management, social barriers, risk aversion)
 3. Infrastructure (i.e. lacking infrastructure to mass-produce and distribute biopesticides, biological control agents and other low-risk compounds)
 4. Industry (e.g. conflicts of interests, distorted information, interference from pesticide industry)
 5. Technology (e.g. immature technology, not adapted to local farming contexts)
 6. Policy (e.g. lack of price support or subsidies for IPM-compatible products, taxation for hazardous chemicals, premium pricing and certification of clean produce, inadequate research back-up, vested interests undermine IPM policy, registration hurdles including weak / unwieldy regulatory environment for biological control)
 7. Culture (e.g. insufficient coordination, lack of interdisciplinary engagement)
- Q9a.** Evaluate the pest management practices of your country's farmers (from 1 to 10, with 1 being ineffective and 10 being very good).
- Q9b.** Regarding the pest management practices of farmers, what should improve?
- Q10.** Rank the degree of pesticide use among your country's farmers (from 1 to 10, with 1 being limited or no use to 10 being overuse).
- Q11.** Estimate the extent of farmers' knowledge of the following IPM technologies (from 1 to 10, with 1 being poor understanding and 10 being very well-understood): a) crop sanitation, b) pest-resistant crop varieties, c) economic thresholds, d) biological control, and e) sampling protocols.
- Q12a.** In your country, are farmers well-informed about sustainable pest management? If not, why?
- Q12b.** In your national pest management programme, is any attention given to farmer education? Please elaborate on the type and reach (number of farmers trained per year) of current extension programmes.
- Q12c.** In your country's pest management programme, are training programmes adapted to the needs of female farmers?
- Q12d.** In your country, are participatory approaches (e.g. farmer field schools) used to promote or validate pest management practices? If yes, how many farmers are involved in such initiatives on an annual basis?

Section III – Concepts and perceptions

- Q13a.** Judge this statement: “Farmers can cause pest outbreaks” – true or false.
- Q13b.** Judge this statement: “Farmers can actively prevent pest outbreaks and thereby avoid pesticide use” – true or false.
- Q13c.** Which farmer management practices favour pest outbreaks? Freely list any practices that make a cropping system more vulnerable to pest attack.
- Q14.** Judge this statement: “Scientists should work hand-in-hand with farmers to resolve pest/disease problems” (from 1 to 10, with 1 being disagree to 10 being fully agree).
- Q15a.** Since the 1960s, IPM has been promoted across the globe. Through a comprehensive, well-funded IPM programme, what percentage reduction in pesticide use might be possible in your country?
- Q15b.** In which crops are large pesticide cuts most feasible?
- Q16a.** Please rank the following in the order of importance when it comes to designing an IPM programme:
1. Resistant or tolerant crop varieties
 2. Crop sanitation and cultural control, e.g. planting date / spacing / crop arrangements
 3. Pesticide resistance management
 4. Pest / disease detection and sampling protocols
 5. Habitat / landscape management
 6. Efficacious pesticides
 7. Spray thresholds and decision criteria
 8. Biopesticides / biological control agents
 9. Mechanical and physical control, e.g. tillage, soil solarization, weeding, trapping
 10. Baseline insights into pest biology / ecology
- Q16b.** Judge this statement: “IPM aims to reduce the use of chemical pesticides” – true or false.
- Q17.** For the following five characteristics, indicate how biological control (and biopesticides) compare to chemical pesticides (-10 biological control is far worse than pesticides, 0 biological control and pesticides perform equally, +10 biological control is considerably better than pesticides):
1. Relative advantage (i.e. degree to which a practice is more productive, efficient, cost-effective, or improves in some other manner upon existing practices)
 2. Compatibility (i.e. degree to which a practice is compatible with existing values, past experiences and farmer needs)
 3. Complexity (i.e. degree to which a practice is perceived as difficult to understand and use)
 4. Observability (i.e. farmers easily observe and evaluate the performance of a new technology)
 5. Trialability (i.e. degree to which farmers can experiment with a new technology on a limited basis, be it by adopting it in part and/or on a temporary basis)

Q18. For the following eight topics, indicate how biological control (and biopesticides) compare to chemical pesticides (-10 biological control is far worse than pesticides, 0 biological control and pesticides perform equally, +10 biological control is considerably better than pesticides):

1. Food safety
2. Biodiversity conservation
3. Human health
4. Clean water
5. Farmer income
6. (Perceived) effectiveness
7. User-friendliness
8. Relative cost and availability

Section IV – Crop protection science and innovation

- Q19.** Provide a rough estimate of the annual budget that is earmarked for crop protection science and innovation in your country (USD per year). This can comprise funds from public, private and international cooperation sectors.
- Q20.** How do you rank your country's capacity to conduct (in-house) applied research in the following domains (from 1 to 10, with 1 being low/no capability and 10 being very well-advanced)?
1. Pest/disease diagnostics and taxonomy
 2. Plant pest/disease epidemiology, including spread forecasting and outbreak prediction
 3. Pest/disease ecology and biology
 4. Agronomy and agro-ecology
 5. Biological control
 6. Host plant resistance breeding / screening
 7. Pesticide efficacy screening
 8. Socio-economic facets of pest management, including farmer education
- Q21.** How do you evaluate the funding status of your country's research activities in the following domains (from 1 to 10, with 1 being critically under-funded and 10 being very well-funded)?
1. Pest/disease diagnostics and taxonomy
 2. Plant pest/disease epidemiology, including spread forecasting and outbreak prediction
 3. Pest/disease ecology and biology
 4. Agronomy and agro-ecology
 5. Biological control
 6. Host plant resistance breeding / screening
 7. Pesticide efficacy screening
 8. Socio-economic facets of pest management, including farmer education
- Q22** For each of the following domains, please list the main source of research budgets. Indicate whether funds are being facilitated by public entities (e.g. government), international development assistance or private sector.
1. Pest/disease diagnostics and taxonomy
 2. Plant pest/disease epidemiology, including spread forecasting and outbreak prediction
 3. Pest/disease ecology and biology
 4. Agronomy and agro-ecology
 5. Biological control
 6. Host plant resistance breeding / screening
 7. Pesticide efficacy screening
 8. Socio-economic facets of pest management, including farmer education
- Q23a.** In your country, is IPM research primarily concentrated on one or few crops? If yes, what crops are being prioritized?
- Q23b.** What percentage share of research attention do these crops receive?
- Q24.** What food / nutrition security crops are being overlooked in (in-country) IPM research? Freely list all crops that lack sufficient / committed / long-term research attention.

Section V – Policy and legislation

- Q25.** Economic thresholds are a core element of IPM. In your country, for which pests / crops have such economic thresholds been defined or validated?
- Q26.** Over the past five years, how many new pesticide active ingredients (AIs) have been registered in your country? Please indicate an approximate number of new AIs per year.
- Q27a.** Across the globe, pesticide over-use is leading to resistance development. What insecticide resistance management practices are being adopted in your country?
- Q27b.** Do your country's resistance management plans involve the active rotation of chemical AIs with biopesticides?
- Q28a.** For new pesticide AIs, do scientists in your country routinely evaluate efficacy, phytotoxicity and residue tests on target agricultural crops under laboratory and/or field conditions?
- Q28b.** Do scientists in your country routinely evaluate the ecological selectivity of new pesticide AIs towards beneficial organisms that are present in local agro-ecosystems? If yes, what beneficial organisms are being tested?
- Q29.** Over the past five years, how many biopesticides and biological control agents have been registered in your country? Please indicate an approximate number of products per year.
- Q30.** At present, which biological control agents and biopesticides are commercially available in your country? Freely list all products that are currently at farmers' disposal.

Appendix II

Survey 2 - Taking the pulse of countries' Fall armyworm mitigation programmes

Section I - Starter

- Q1a.** Over the past two years, fall armyworm (FAW) has made its arrival in your country. List the three crops in which FAW is frequently recorded.
- Q1b.** Maize is widely seen as the preferred host plant of FAW in its invaded range in Asia. In your country, please estimate the following four features of the FAW invasion. Provide concrete estimates, either in percentages or in USD.
1. Geographic distribution (i.e. percentage of maize area affected)
 2. Field-level incidence (i.e. percentage of plants infected / damaged)
 3. Yield loss (i.e. percentage of lower productivity)
 4. Management costs (i.e. USD financial expenditure for pest control, per hectare and year)
- Q2.** As compared to other native or invasive pests in your country, how does FAW rank on the following characteristics? For each characteristic, indicate with a figure between -10 and +10 whether FAW poses a lesser or greater severe threat than other pests (-10 FAW is considerably less of a threat than other endemic pests, 0 FAW and other endemic pests perform equally, +10 FAW is considerably more of a threat than other endemic pests).
1. Geographic distribution
 2. Field-level incidence (i.e. percentage of plants infected / damaged)
 3. Yield loss (i.e. percentage of lower productivity)
 4. Farmer livelihood impacts (e.g. income loss)
 5. Direct or indirect environmental impacts
- Q3.** Judge the following statements (rank the relevance of each statement on a scale from 1 to 10, with 1 being irrelevant and 10 being very relevant):
1. In my country, FAW poses a major threat to food and livelihood security.
 2. In my country, FAW feeding damage is extensive but yield impacts are low to moderate.
 3. The current emphasis on FAW obscures other (more or equally) severe pests.

- Q4a.** Evaluate the current status of your country's FAW mitigation programme from 1 to 10, with 1 being rather weak or immature and 10 being very solid and comprehensive.
- Q4b.** In your country's FAW mitigation programme, what attention is being given to the following constituent components? Rank the seven components in order of the degree of attention they receive in the national FAW programme.
1. Systematically reviewing the global literature on FAW biology, ecology and management
 2. Acquiring basic insights on FAW biology and ecology
 3. Taxonomic identification and strain delineation
 4. Monitoring and characterization of spread dynamics
 5. Quantifying yield losses and economic impacts
 6. Devising and validating management approaches
 7. Farmer education and technology transfer
- Q5.** Freely list any and every notable insight, scientific advance and/or innovation related to FAW mitigation that has been achieved in your country. What pioneering work on FAW surveillance, prevention and control has been carried out?
- Q6.** On what topics is international assistance desired / required?

Section II – FAW identity, biology and ecology

- Q7.** Please indicate the progress your country has made in the following domains (from 1 to 100, with 1 being limited or no progress to 100 being major advances)
1. Ascertaining taxonomic identity
 2. Characterization of FAW life cycle and description of individual life stages
 3. Description of population phenology in one or more agro-ecological zones
 4. (Molecular) elucidation of FAW host strains and/or pesticide resistance profiles
 5. Confirming FAW feeding on local agricultural / non-crop hosts, including crop varieties
 6. Description of FAW feeding damage on different maize developmental stages
 7. Quantification of climatic impacts on FAW development
 8. Characterization of associated natural enemies in prevailing agro-ecologies
 9. Description of the effects of field-level agronomic interventions (e.g. plant spacing, fertilization, irrigation, tillage) on FAW prevalence
 10. Understanding of landscape-level interactions
- Q8.** Please indicate the domains for which there is sufficient / credible scientific expertise in your country.
1. Insect taxonomy
 2. Characterization of insect life cycle / life stages
 3. Description of (in-field) population phenology
 4. (Molecular) elucidation of FAW host strains and/or pesticide resistance profiles
 5. Confirming insect feeding on agricultural / non-crop hosts, including crop varieties
 6. Description of insect feeding damage on crops
 7. Quantification of climatic impacts on insect development
 8. Characterization of natural enemies in farm settings
 9. Description of the effects of field-level agronomic interventions (e.g. plant spacing, fertilization, irrigation, tillage, intercropping) on FAW prevalence
 10. Understanding of landscape-level interactions
- Q9.** Please outline the areas – solely related to FAW identity, biology, ecology – in which international support is desired / required.
- Q10a.** Is there any concern that invasive FAW populations in your country are resistant to certain pesticide AIs? Yes/no.
- Q10b.** Is there concrete evidence that invasive FAW populations in your country are resistant to certain pesticide AIs?
Please list all AIs for which resistance has been shown.
- Q11.** Judge the following statement: “In light of FAW management, it is important to understand the effects of agronomic interventions (e.g. tillage, mulching or fertilization).” Rank the relevance of this statement from 1 to 10, with 1 being irrelevant and 10 being very relevant.
- Q12a.** Estimate the share (percentage) of farmers in your country that possess at least a basic understanding of FAW biology and natural enemies.
- Q12b.** Please provide a full listing of FAW natural enemies (e.g. arthropods, viruses, fungi) that have been formally identified in your country.

Section III – Monitoring and field scouting

Q13. Please indicate the progress your country has made in the following domains (from 1 to 100, with 1 being limited or no progress to 100 being major advances).

1. Training extension officers and plant protection officers on FAW detection
2. Distributing pheromone traps among FAW-affected farmers
3. Systematically tracking FAW pressure over space and time, across the national territory
4. Using monitoring or trapping data for forecasting / prediction purposes
5. Formally relating in-field pest pressure to (pheromone) trap captures
6. Evaluating the use of bait substances / UV light for monitoring purposes
7. Defining (standardized) field scouting protocols
8. Establishing a centralized monitoring data portal and/or FAW early-warning system
9. Educating farmers about FAW detection, including trapping and scouting tools
10. Exploring the use of remote sensing, radar and drone-based approaches

Q14. Please indicate the domains for which there is sufficient / credible (scientific) expertise in your country.

1. Training extension officers and plant protection officers
2. Distributing pheromone traps among farmers
3. Systematically tracking pest pressure over space and time
4. Using monitoring or trapping data for forecasting / prediction purposes
5. Formally relating in-field pest pressure to (pheromone) trap captures
6. Evaluating the use of bait substances / UV light for monitoring purposes
7. Defining (standardized) field scouting protocols
8. Establishing a centralized monitoring data portal and/or early-warning system
9. Educating farmers about pest detection, including trapping and scouting tools
10. Exploring the use of remote sensing, radar and drone-based approaches

Q15. Please outline the areas – pertaining to FAW monitoring and field scouting – in which international support is desired / required.

Q16a. Across the national territory, please indicate the share (percentage) of cropping areas in which FAW monitoring is carried out in a systematic, regular fashion.

Q16b. At what frequency is monitoring done (daily, weekly, monthly, 2/year)?

Q17. Have your country's FAW monitoring data been related to biophysical / meteorological parameters? If yes, what are the determinants of FAW outbreaks?

Q18a. Estimate the share (percentage) of your country's farmers that are well-informed about FAW detection, including trapping and field scouting protocols.

Q18b. Estimate the share (percentage) of your country's farmers that actually deploy traps and/or use scouting data to guide their pest management decisions. For example, farmers can decide to spray biopesticides based upon the number of FAW moths that are caught weekly in pheromone traps.

Section IV – FAW prevention and control

Q19. Please indicate the progress your country has made in the following domains (from 1 to 100, with 1 being limited or no progress to 100 being major advances).

11. Selecting FAW-resistant or tolerant crop varieties, including GM maize
12. Examining cultural control schemes, e.g. planting date / spacing / intercrop arrangements
13. Developing insecticide resistance management plans
14. Validating habitat / landscape management tactics, e.g. flower strips, beetle banks
15. Validating the efficacy of different pesticide active ingredients
16. Exploring the use of FAW semiochemicals in mating confusion
17. Establishing spray thresholds and decision criteria
18. Evaluating biopesticides under field / laboratory conditions
19. Assessing different mechanical control options, e.g. tillage, soil solarization, trapping
20. Characterizing ecological requirements of FAW natural enemies

Q20. Please indicate the domains for which there is sufficient / credible scientific expertise in your country.

1. Selecting / evaluating pest-resistant or tolerant crop varieties
2. Examining cultural control schemes, e.g. planting date / spacing / intercrop arrangements
3. Developing insecticide resistance management plans
4. Validating habitat / landscape management tactics, e.g. flower strips, beetle banks
5. Validating the efficacy of different pesticide active ingredients
6. Exploring the use of semiochemicals for pest control, e.g. mating confusion
7. Establishing spray thresholds and decision criteria
8. Evaluating biopesticides under field / laboratory conditions
9. Assessing mechanical control options, e.g. tillage, soil solarization, trapping
10. Characterizing ecological requirements of natural enemies

Q21. Please outline the areas – pertaining to FAW prevention and control – in which international support is desired / required.

Q22a. Please indicate what FAW management practices are commonly adopted by farmers in your country. Rank the below practices from the most common (top) to the least common (bottom).

1. Establish an intercrop in maize
2. Set up (pheromone, light, baited) traps in maize fields
3. Do nothing
4. Grow FAW-tolerant varieties
5. Periodically apply chemical pesticides
6. Manually control FAW larvae, e.g. by hand crushing
7. Use insecticide-coated seeds at the time of planting
8. Release and/or protect natural enemies

- Q22.** Has pesticide use in maize increased following the FAW invasion? If yes, estimate the percentage increase as compared to pre-invasion levels.
- Q23.** Biological control can be a most cost-effective management solution, for invasive and native pests alike. To advance FAW biological control, what progress has been made in your country on the following fronts. Please rank progress from 1 to 100, with 1 being limited or no progress to 100 being well-advanced.
1. Discover and describe biodiversity in farm settings, e.g. identify insect predators in FAW-affected maize fields.
 2. Elucidate key life history parameters of natural enemies, e.g. fecundity, longevity, predation rate, environmental adaptability.
 3. Characterize the population ecology of FAW natural enemies, e.g. life table analysis, exclusion cage studies, dietary assessment.
 4. Examine ways to mobilize on-farm biodiversity for biological control, e.g. through establishing flower strips, beetle banks, crop diversification.
 5. Develop and refine natural enemy mass-rearing / packaging and distribution / release schemes.
 6. Transfer of biological control information to end-users, e.g. farmers.
 7. Assess social-ecological outcomes, e.g. product quality, yield, farm income, environmental health.
- Q24a.** In your country, please indicate the extent of scientific attention to the following FAW biological control agents. For each organismal group, rank scientific progress from 1 to 100, with 1 being limited or no progress to 100 being well-advanced.
1. Invertebrate predators
 2. Invertebrate parasitoids
 3. Vertebrate predators, e.g. birds, bats, rodents, frogs
 4. Viruses, fungi and bacteria (microbials)
 5. Nematodes (macrobials)
- Q24b.** In your country, please indicate the extent of scientific attention to the following biological control approaches, specifically aimed at FAW management. For each approach, rank scientific progress from 1 to 100, with 1 being limited or no progress to 100 being well-advanced.
1. Conservation biological control, i.e. the in-field conservation and population enhancement of naturally-occurring beneficial organisms.
 2. Augmentation biological control, i.e. the periodic release of laboratory-reared beneficial organisms (including spray application of FAW-killing fungi or viruses).
 3. Classical biological control, i.e. the scientifically-guided introduction of exotic natural enemies.
- Q24c.** Does your country consider the introduction of non-native (i.e. exotic) organisms for FAW management, e.g. host-specific parasitic wasps from the FAW region of origin? Yes/no.

Section V – Farmer extension and participatory research

- Q25.** Judge this statement: “There is a lot to be gained if scientists can work hand-in-hand with farmers to resolve FAW pest problems” (from 1 to 10, with 1 being disagree to 10 being fully agree).
- Q26a.** Evaluate the current status of FAW management by farmers in your country (from 1 to 10, with 1 being ineffective and 10 being very good).
- Q26b.** Regarding FAW management by farmers in your country, what should improve?
- Q27.** Please rate the extent of farmer knowledge / understanding in your country regarding the following set of FAW management practices (from 1 to 100, with 1 being limited or no understanding to 100 being very advanced knowledge).
1. FAW-resistant or tolerant crop varieties, including GM maize
 2. Cultural control, e.g. planting date / spacing / intercrop arrangements
 3. Insecticide resistance management
 4. On-farm presence of beneficial organisms
 5. Application mode of chemical insecticides
 6. Use of FAW semiochemicals for trapping or mating confusion
 7. Insecticide spray thresholds and decision criteria
 8. Biopesticide application, e.g. nucleopolyhedroviruses (NPV)
 9. Mechanical control, e.g. hand-crushing tillage, soil solarization, trapping
 10. In-field conservation of predatory insects or parasitoids, e.g. with flower strips, beetle banks
- Q28.** For each of the above FAW management practices, indicate which ones receive priority attention in your country's extension programme.
1. FAW-resistant or tolerant crop varieties, including GM maize
 2. Cultural control, e.g. planting date / spacing / intercrop arrangements
 3. Insecticide resistance management
 4. On-farm presence of beneficial organisms
 5. Application mode of chemical insecticides
 6. Use of FAW semiochemicals for trapping or mating confusion
 7. Insecticide spray thresholds and decision criteria
 8. Biopesticide application, e.g. NPV
 9. Mechanical control, e.g. hand-crushing tillage, soil solarization, trapping
 10. In-field conservation of predatory insects or parasitoids, e.g. with flower strips, beetle banks
- Q29.** Estimate the ratio of public-funded extension officers versus pesticide sellers / industry-funded crop advisors in your country.
- Q30.** What is needed to extend the reach and impact of your country's FAW management programme?
What needs to be done to achieve farmer behavioural change at scale?

Section VI – Policy and regulation

- Q31.** Does your country have a coordination mechanism in place to deal with emerging pests, e.g. a task force with a national > local command chain covering a suite of activities from research to extension.
Or are emerging pests tackled on an ad hoc basis?
- Q32a.** In your country, which pesticide AIs have been officially registered for use against FAW? Provide a full listing of AIs.
- Q32b.** For newly registered pesticides, which parameters have been evaluated by in-house experts in your country?
1. Product performance – efficacy against FAW under laboratory conditions
 2. Product performance – efficacy against FAW under field conditions
 3. Hazard assessment for humans and domestic animals
 4. Hazard assessment for non-target organisms
 5. Post-application / applicator exposure
 6. Pesticide spray drift
 7. Environmental fate
 8. Other (please specify)
- Q33a.** Across the globe, FAW resistance has been recorded for at least 41 active ingredients. Please describe the insecticide resistance management plan that is in place in your country. Briefly list its core components.
- Q33b.** Do your country's resistance management plans involve the active rotation of chemical AIs with biopesticides?
Yes/no.
- Q34a.** Across the globe, several biopesticides have proven to be very effective against FAW. Since the FAW invasion in your country, how many biopesticides and biological control agents have been registered in your country?
- Q34b.** In your country, which biological control agents and biopesticides are commercially available for use against FAW?
Freely list all products that are currently at farmers' disposal.
- Q34c.** Experiences from around the world show that biopesticides (and egg parasitoids, for example) can easily be produced in small-scale, family production units (so-called cottage industries). Do these production units exist in your country?
What (government) support do they receive?
- Q34d.** Does your country have capacity for biopesticide registration and quality control?
- Q35a.** What policy measures can facilitate the use of biological control agents and biopesticides against FAW?
Are there any incentives coded in national policies to prioritize agro-ecological or biopesticide management?
Please define any policy measures that might prove useful.
- Q35b.** What policy measures are needed to reduce farmers' dependency on synthetic pesticides for FAW management? Please define any policy measures that might prove useful.

Appendix III

Table 1. Key attributes of technological innovations, as defined in Rogers' diffusion of innovations theory (Rogers, 1962).

Attribute	Description
Relative advantage	Degree to which a practice is more productive, efficient, cost-effective, or improves in some other manner upon existing practices
Compatibility	Degree to which a practice is compatible with existing values, past experiences and farmer needs
Complexity	Degree to which a practice is perceived as difficult to understand and use
Observability	Stakeholders (e.g. farmers) easily observe and evaluate the performance of a new technology
Trialability	Degree to which stakeholders can experiment with a new technology on a limited basis, be it by adopting it in part and/or temporarily

Table 2. Description of the alphanumeric codes for 10 different scientific domains that relate to FAW identity, biology and ecology (see Figure 13).

Code	Scientific domain
I1	Ascertaining FAW taxonomic identity
I2	Characterization of FAW life cycle and description of individual life stages
I3	Description of population phenology in one/more agro-ecological zones
I4	(Molecular) elucidation of FAW host strains and/or pesticide resistance profiles
I5	Confirming FAW feeding on local agricultural / non-crop hosts, including crop varieties
I6	Description of feeding damage on different maize developmental stages
I7	Quantification of climatic impacts on FAW development
I8	Characterization of associated natural enemies in prevailing agro-ecologies
I9	Description of the effects of agronomic interventions (e.g. plant spacing, fertilization, tillage, intercropping) on FAW prevalence
I10	Understanding of landscape-level interactions

Table 3. Description of the alphanumeric codes for 10 different domains that relate to FAW monitoring and in-field scouting (see Figure 15).

Code	Scientific domain
M1	Training extension officers and plant protection officers on FAW detection
M2	Distributing pheromone traps among FAW-affected farmers
M3	Systematically tracking FAW pressure over space and time, across the national territory
M4	Using monitoring or trapping data for forecasting / prediction purposes
M5	Formally relating in-field pest pressure to (pheromone) trap captures
M6	Evaluating the use of bait substances / UV light for monitoring purposes
M7	Defining (standardized) field scouting protocols
M8	Establishing a centralized monitoring data portal and/or FAW early-warning system
M9	Educating farmers about FAW detection, including trapping and scouting tools
M10	Exploring the use of remote sensing, radar and drone-based approaches

Table 4. Description of the alphanumeric codes for 10 different domains that relate to FAW prevention and control (see Figure 17).

Code	Scientific domain
C1	Selecting / evaluating FAW-resistant or tolerant crop varieties, including GM maize
C2	Examining cultural control schemes, e.g. planting date / spacing / intercrop arrangements
C3	Developing insecticide resistance management plans
C4	Validating habitat / landscape management tactics, e.g. flower strips, beetle banks
C5	Evaluating the efficacy of different pesticide active ingredients
C6	Exploring the use of FAW semio-chemicals in mating confusion
C7	Establishing spray thresholds and decision criteria
C8	Evaluating biopesticides under field / laboratory conditions
C9	Assessing mechanical control options, e.g. tillage, soil solarization, trapping
C10	Characterizing ecological requirements of FAW natural enemies

Table 5. Description of the alphanumeric codes for 10 different domains that relate to FAW extension and participatory research (see Figure 20).

Code	Scientific domain
E1	FAW-resistant or tolerant crop varieties, including GM maize
E2	Cultural control, e.g. planting date / spacing / intercrop arrangements
E3	Insecticide resistance management
E4	On-farm presence of beneficial organisms
E5	Application mode of chemical insecticides
E6	Use of FAW semiochemicals for trapping or mating confusion
E7	Insecticide spray thresholds and decision criteria
E8	Application of biopesticides, e.g. NPV, nematodes
E9	Mechanical control, e.g. hand-crushing tillage, soil solarization, trapping
E10	In-field conservation of predatory insects or parasitoids, e.g. with flower strips, beetle banks

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