Review Article

CURBING GREENHOUSE GAS (GHG) EMISSIONS THROUGH BIODIVERSITY-DRIVEN CROP PROTECTION: BRIGHT PROSPECTS FOR THE ASIA-PACIFIC

Yubak G.C.[1], Michael J. Furlong[2] and Kris A.G. Wyckhuys[3]

[1]FAO Regional Office, Bangkok
[2]University of Queensland, Australia
[3]Chrysalis Consulting, Belgium
Correspondence: yubak.gc@fao.org

ABSTRACT

Synthetic pesticides are widely used in Asian agriculture to manage crop insect pests, diseases, and weeds. The overreliance on these toxic compounds negatively affects human health, biodiversity, and farm profits, while contributing to climate change. Pesticide-centered crop protection is highly energy-intensive, with product synthesis, distribution, and field application generating substantial greenhouse gas (GHG) emissions. In countries such as China, Malaysia, or Japan, chemical pesticide use thus causes carbon emissions equivalent to those of a respective 1.7 million, 381,000, or 300,000 passenger vehicles. As the foundation of integrated pest management (IPM), biological control and agroecology constitute practicable, cost-effective, and efficacious alternatives to synthetic pesticides. These carbon-efficient measures safeguard food and nutrition security without concomitant negative impacts on human health, biodiversity, or environmental degradation. Over the past decades, several Asian countries have already gained ample experience with non-chemical pest management and consolidated important techno-scientific capacity. Yet, all too often, these scientific advances are not translated into practice. Here, we show how a bundle of policy options (e.g., carbon financing) can further take biodiversity-driven pest management to scale across the Asia-Pacific region.

Key words : Biodiversity, biological control, carbon financing, carbon emission, climate change, IPM

INTRODUCTION

The food system roughly accounts for one-third of the world's greenhouse gas (GHG) emissions (Rosenzweig et al., 2020; Crippa et al., 2021), which are largely attributed to the on-farm production of livestock and crops (i.e., farming), and agriculture-driven land-use change (Rosenzweig et al., 2020). Over the past 30 years, these emissions have risen exceptionally fast in developing regions such as Asia – where agricultural mechanization, land-use change, and increased use of synthetic inputs are prime drivers (Crippa et al., 2021). At present, countries such as Indonesia, Laos and Cambodia experience near-exponential increases in pesticide use intensity (Schreinemachers et al., 2017).

In order to draw suitable mitigation trajectories, GHG emissions of the agriculture sector need to be quantitatively assessed. N_2O emissions from N fertilizer application and methane emissions from rice are important contributors to cropland emissions, with the latter especially relevant in Asian rice bowls such as Vietnam (Carlson et al., 2017). On the other hand, synthetic pesticides are well-recognized drivers of biodiversity loss, but their carbon emissions are rarely assessed (Heimpel et al., 2013). As a result, low-carbon alternatives to pesticide-centered crop protection receive scant attention and anemic levels of funding. Further, pesticide reduction rarely features in global or national climate change mitigation programs.

Building upon a recently published assessment (Wyckhuys et al., 2022), we report the carbon footprint of pesticide manufacture, distribution and application across the Asia-Pacific region (Table 1). This footprint is habitually expressed as carbon equivalent (CE) or CO_2 equivalent. Countries with high (pesticide-related) emissions are, in declining order of magnitude: China (2.1 million t CE), Russia (558,000 t), Australia (544,000 t), Malaysia (482,000 t) and Japan (379,000 t). In China, these carbon emissions are equivalent the annual outputs of 2.1 coal-fired power stations or 1.7 million passenger vehicles. Importantly, large agricultural producers such as India and Iran exhibit comparatively small (pesticide-related) footprints. Meanwhile, for countries such as Vietnam or Indonesia, official pesticide usage data are critically outdated and the related carbon emissions are thus likely gross under-estimates of the current situation. Also, curated databases such as FAOSTAT (www.faostat.org) do not contain usage statistics of countries such as Pakistan. Lastly, while pesticidal seed treatments are increasingly adopted, these are only reported by a few Asian countries. Though the carbon-efficient nature of such application modes is often touted, seed coatings with systemic insecticides are rarely warranted and degrade the ecological resilience of farmland. All too often, this pre-emptive use of pesticides worsens pest issues and lowers farmers' profit margins (Douglas & Tooker, 2015).

All emissions estimates are highly conservative, as new pesticidal compounds tend to be more energy-intensive than older ones, solvents are more extensively used, and mechanical application modes have become increasingly popular (Crippa et al., 2021). More precise values (e.g., on active ingredients or fine-resolution application data) could however guide effective decision-making and help to target mitigation efforts at national and regional levels.

METHODOLOGY

This review article is based on the review of policy-related manuscripts on carbon foot print, ecological pest management, carbon financing, nature-based solutions published in various policy-related publications such as journals, books, periodicals, proceedings, and the Internet.

RESULTS AND DISCUSSION

Agroecological and biodiversity-based solutions

To decarbonize Asia-Pacific agriculture and thus slow global warming, far-reaching 'transformational' change is required. The 'solutions space' for pesticide phase-down ranges from 1) an improvement in usage efficiency, 2) a direct substitution of pesticidal compounds with non-chemical alternatives, and 3) an overarching redesign of entire farming systems (Vanbergen et al., 2020). By carefully choosing alternative management schemes, one can sustainably intensify farming systems, conserve or reconstitute ecosystem function, and reduce energy needs and thus carbon emissions. Two different approaches that are particularly relevant to efforts to reduce pesticidal inputs are biological control (i.e., the informed introduction, conservation, or augmentation of pestkilling organisms such as insect predators, parasitic wasps, or beneficial microorganisms; Bale et al., 2008; Mason, 2021) and agroecology (i.e., the judicious application of ecological principles in agriculture; Tomich et al., 2011). Both tactics are foundational components of integrated pest management (IPM), a sequential decision-making process that aims to reduce pest-induced crop losses with minimal or zero reliance upon synthetical pesticides.

Table 1. Carbon footprint of pesticide use in the Asia-Pacific region

Country	Carbon emissions (tonnes CE)		Passenger vehicles driven (thousands)	Barrels of oil consumed (thousands)
	Average	Range		
Australia	544,277	169,742-1,013,505	430	4,620
Bangladesh	96,428	33,949-181,678	76	819
Bhutan	50	16-95	0.0	0.4
Brunei Darussalam	179	56-343	0.1	2
China	2,144,771	683,850-3,894,343	1,694	18,207
Taiwan	77,595	24,821-142,569	61	659
Cook Islands	26	8-48	0.0	0.2
Fiji	4,824	1,459-8,378	4	41
French Polynesia	221	69-414	0.2	2
India	295,084	93,517-511,252	233	2,505
Indonesia[a]	11,755	3,603-20,017	9	100
Iran	35,181	11,499-62,508	28	299
Japan	379,313	123,505-686,478	300	3,220
Laos	25	8-48	0.0	0.2
Malaysia	482,101	151,754-922,185	381	4,093
Maldives	2,490	749-3,977	2	21
Mongolia	947	299-1,823	0.7	8
Myanmar	117,161	37,176-213,007	93	995
Nepal	4,114	1,345-7,455	3	35
New Caledonia	95	30-182	0.0	0.8
New Zealand	37,254	12,079-71,471	29	316
Papua New Guinea	978	306-1,894	0.8	8
Philippines	50,863	16,787-95,206	40	432
Republic of Korea	136,445	43,666-245,998	108	1,158
Russia	558,290	182,124-1,055,911	441	4,739
Samoa	1,079	338-2,090	0.9	9
Sri Lanka	14,409	4,807-27,113	11	122
Thailand	280,098	84,514-483,122	221	2,378
Timor Leste	17	5-30	0.0	0.1
Tonga	151	49-287	0.1	1
Vanuatu	911	274-1,488	0.7	7
Vietnam[a]	143,371	45,164-249,403	113	1,217

Calculations are based upon country-level usage data of insecticides, fungicides and bactericides, and herbicides (including seed treatment), extracted from FAOSTAT (www.faostat.org) and averaged over 2016-2018 (Wyckhuys et al., 2022). Greenhouse gas equivalencies are calculated using the online toolkit of the Environmental Protection Agency (EPA; https://www.epa.gov/energy/ greenhouse-gas-equivalencies-calculator). An official pesticide usage data not updated for >10 years

Some of the earliest origins of biological control can be traced to the Asia-Pacific. For centuries, citrus and mango growers in China, Myanmar, and Vietnam have successfully used resident carnivorous ants for pest management (Fig. 1). In grasslands of northwestern China, farmers have built artificial birdhouses and shelters to conserve rosy starling populations for grasshopper control (Olkowski & Zhang, 1998). Though these measures are prime examples of traditional knowledge and farmer-led innovation, biological control and agroecology have also been scientifically scrutinized for decades. Indeed, pesticide-intensive nations such as Australia, India, New Zealand, Iran, and Pakistan possess a rich scientific literature on biological control (Fig. 2). Similarly, countries such as India, Australia, Japan, and Bangladesh can bank on (comparatively) long agro-ecology research trajectories. During the 1980-90s, this research was put into practice through UN-backed pesticide reduction programs that employed farmer field school (FFS) training approaches (Van den Berg & Jiggins, 2007; Waddington et al., 2014). Comprehensive FFS campaigns centered on several pesticide-intensive crops including rice, cotton, tea, and vegetables. In countries such as the Philippines, Indonesia, and Vietnam, millions of farmers discovered the ecological underpinnings of agriculture, gained first-hand expertise with non-chemical crop protection alternatives, and were able to cut pesticide use by 70-90% on their farm premises.

The carbon mitigation potential of these scientifically underpinned tactics is considerable. By reducing the number of pesticide spray applications in rice or vegetables, Asian FFS programs lowered GHG emissions by a respective 5.6-16.8 kg CE and 0-33.5 kg CE per hectare and season. These values are of a similar order as those of New Zealand's horticulture sector, where pesticide use annually accounts for 118 kg CE per hectare (Safa & Watts, 2014). By extrapolating the above reductions to the entire domestic acreage of certain crops, IPM thus averted carbon emissions of 160-180,000 t CE per year in rice crops in Indonesia, Vietnam, and Thailand and by 250,000 t CE in Indian cotton. Thus, by pairing a pesticide phase-down with concerted efforts to mitigate methane emissions (in rice), the climate change impact of Asia's agriculture sector could be greatly reduced.

Pesticide-free crop protection generates significant additional benefits, which can help countries achieve the UN Sustainable Development Goals (SDGs). Following FFS training in 1990, millions of Asian farmers reduced pesticide usage and concurrently raised crop yields by an average of 13%. FFS campaigns in local rice, cotton, and vegetable crops resulted in 4-25% yield increases and augmented farm revenue by nearly 20%. Non-chemical pest avoidance strategies are especially appealing, as they can greatly reduce the economic costs of crop protection. Pesticide applications are expensive, habitually used in irrational and unguided manners, and often prove entirely unnecessary. In high-value crops such as vegetables and fruits, Southeast Asian farmers tend to overspend hundreds of dollars per hectare and season on these agrochemicals (Schreinemachers et al., 2020). The same occurs when farmers try to tackle invasive pests or diseases, as evidenced by 300% increases in insecticide usage following the invasion of the fall armyworm (Yang et al., 2021). As such, pesticide-centered tactics skim household incomes, deepen poverty vulnerability, and hamper rural development. In alternative approaches, the deployment of agroecological techniques and the harnessing of biodiversity for pest control (Landis et al., 2000) can lead to reduced farm-level expenditures and an increase in farmers' purchasing power. These economic benefits have been demonstrated in various Asian production contexts. By growing flowering plants on rice bunds in Vietnam or Thailand, insecticide applications can be reduced by 70% while yield and profit are raised by 5-7.5% (Gurr et al., 2016). Seed mixtures of disease-susceptible and disease-resistant rice varieties can provide near-total control of debilitating diseases, boost yields by 89%, and abolish the need for fungicidal sprays (Zhu et al., 2000). Diversifying Indian or Chinese cotton systems with food crops such as buckwheat or maize can secure cost-free pest control e.g., by augmenting populations of beneficial arthropods (Li et al., 2019; Pan et al., 2020). Similar benefits can be reaped through the deployment of inter- or cover-crops in cassava or coffee (Delaquis et al., 2018; da Consolacao Rosado et al., 2021), and growing cacao under agroforestry arrangements can mitigate weed problems and raise returns on labor by 41% (Armengot et al., 2016).

Low-carbon crop protection also fortifies a broader bundle of ecosystem services including water conservation, pollination, carbon sequestration or soil health. Ecological infrastructures such as hedgerows or beetle banks, cover crops etc, boost carbon sinks, reduce soil erosion, fix atmospheric nitrogen, and represent a true boon for on-farm biodiversity (Tamburini et al., 2020). The latter is particularly relevant in the Yellow River, Indus or Mekong, and Red River Basins (Tang et al., 2021), where pesticide usage intensity is exacerbated, and its biodiversity impacts are compounded by water scarcity. Management schemes that harness biodiversity for pest, disease or weed control thus check all the boxes of an effective 'natural climate solution' (Cook-Patton et al., 2021).

Fig. 1. For centuries, fruit growers in China, Myanmar, and Vietnam have refined the practice of biological control. By nurturing *Oecophylla* spp. ant colonies in fruit orchards, local farmers have learned to manage pests without the need to resort to synthetic pesticides. Photo credits: Paul van Mele (AgroInsight, YEAR?).

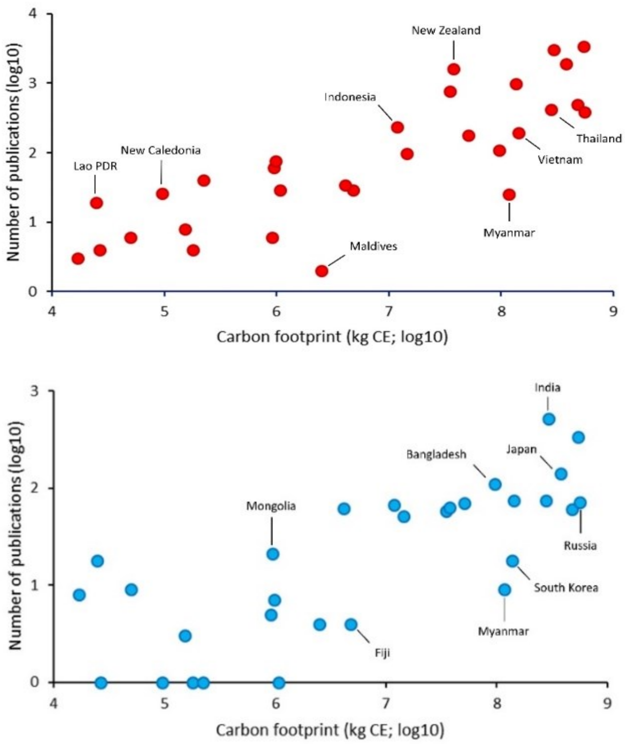

Fig. 2. Countries' techno-scientific capacity for biodiversity-driven crop protection as contrasted with the carbon footprint (kg CE) of domestic pesticide use.

For 30 Asia-Pacific nations, techno-scientific capacity (Y axis) is determined by logging the number of peer-reviewed scientific publications on biological control (upper panel; red dots) or agro-ecology (lower panel; blue dots). Total scientific output is assessed over 1900-2017 using Web of Science (WoS; Wyckhuys et al., 2022). Log-transformed values are plotted. Overall, countries with high (pesticide-related) GHG emissions possess substantial techno-scientific capacity in biodiversity-driven crop protection. Selected countries are listed in each graph.

Key messages to reduce carbon emission and integrate biodiversity and ecology-based pest management strategies by developing financing models & policy tools

In order to take low-carbon pest management to scale, supportive policies and suitable funding schemes are needed (Wyckhuys et al., 2022). Below, we explore some ideas that could be considered by government decision-makers or other (agri-food system) actors. Ideally, a bundle of policy interventions is to be put in place to synergistically facilitate the uptake of agroecological measures and ultimately eliminate irrational pesticide use.

Carbon financing

When exploring options to decarbonize Asian economies, agroecological crop protection constitutes an appealing investable proposition. Drastic reductions in pesticide use yield real, immediate, and verifiable reductions of GHG emissions – which equal hundreds of thousands of tonnes CE per year for several countries (Table 1). The decarbonization potential of low-carbon crop protection can be unlocked by directing funds through different modalities: carbon markets, payment for ecosystem services (PES), natural capital investment or capital earmarked for low-carbon investment (Bridge et al., 2020). As the credibility, effectiveness and validity of afforestation (i.e., the establishment of new, permanent forests) is often questioned, measures such as biological control could be inserted into (voluntary, regulatory) carbon offset schemes for governments or private sector actors such as the aviation industry. Inspiration can also be drawn from PES by calculating the extent to which pesticides depreciate the monetary value of (natural) biological control in given crops, watersheds or broader geographies. These values can be substantial, for example in US farmland insect biological control services worth an estimated US$ 4.5 billion per year (Losey & Vaughan, 2006). Various actors can also direct funding streams towards natural capital for carbon sequestration; the establishment of buffer strips or hedgerows on individual farms or entire landscapes not only helps to fix atmospheric carbon, but also avoids pest population build-up or disease proliferation. Similarly, farmers or land managers who consciously implement residue mulching, cover cropping, mix farming, intercropping, creating a fallow land “beetle banks” or conservation tillage can be financially rewarded for climate change mitigation and (indirect) pesticide avoidance.

Tailored subsidies and taxation schemes

In Asia and across the globe, hundreds of small-sized commercial enterprises and cottage-industry operations mass-produce biological control agents (Van Lenteren et al., 2018). In countries such as China, Russia, and Vietnam, minute parasitic wasps, insect-killing bacteria or antagonistic fungi are cultured at comparatively low cost in laboratories for subsequent deployment on farmland, often at low or no cost to individual growers. Other enterprises also advance pesticide-free crop protection by developing (autonomous) robotic weeders, behavior-modifying chemicals, antibody technologies, or decision aids. When carefully designed, tax breaks, custom-made taxes, privilege loans, or subsidies can support these companies.

Hard policy options or “command and control” measures can involve conditional financial assistance to farmers, pesticide taxes, or even chemical product bans (Möhring et al., 2020). In a similar way as taxes on fat, junk food, or sweetened beverages, taxation can be designed to discourage the use of synthetic pesticides. Such taxation schemes can be justified by alluding to the carbon footprint of pesticides and their broader impacts on human health, biodiversity and ecosystem functioning. Also, these measures are most effective when their spill-over benefits and ultimate policy goals are clearly communicated, and tax revenues are earmarked for agriculture-related spending. Regulatory caps (i.e., on pesticide volume, usage intensity or toxicity loading) or emissions pricing can be paired with the above measures.

Farmer education and awareness-raising

Farmers across the globe have a deficient understanding of the biology, ecology or mere existence of biological control agents. As a result, they undervalue the contribution of natural (pest, disease) population regulation and over-estimate pest- or disease-induced losses. Farmers’ incomplete (agro-ecological) knowledge thus hampers innovation, leads to a so-called ‘pesticide lock-in’ and stifles the broader diffusion of agro-ecological practices (Wyckhuys et al., 2019). All too often, farmers’ decisions to apply pesticides are not economically sound but are instead guided by ‘worst case’ scenarios and further reinforced by the marketing campaigns of agrochemical suppliers. As exemplified through the Farmer Field School programs, hands-on, discovery-based learning can counteract this phenomenon and ease a transition towards reduced pesticide inputs. Through a sequence of field visits with a trained facilitator, FFS lets farmers discover different beneficial organisms, and on-farm ecological processes and gain familiarity with non-chemical management strategies.

Carefully designed farmer training schemes can be coupled with insurance schemes that cover unforeseen shortfalls or eventual pest outbreaks. These programs have proven to be effective in Italian maize productions (Veres et al., 2020), where individual growers or farmer associations can join mutual funds and purchase coverage at the yearly cost of a few dollars per hectare. By doing so, one can actively engage loss- or risk-averse farmers and resource-poor smallholders. The initial establishment of such insurance schemes and full-fledged training programs can be enabled through carbon finance, pesticide taxation or integrated rural development programs. To ensure the success of the above initiatives and to ensure farmers' access to impartial information, it is essential to decouple pesticide sales from farm-level advisories. All these measures, when taken in concert, can achieve concrete reductions in pesticide use, slow global warming and deliver a broad suite of social-environmental outcomes.

CONCLUSIONS

In Asian agriculture, synthetic pesticides constitute the primary means of crop protection. Pesticide use is highly energy intensive and expands the carbon footprint of agriculture. By phasing down pesticide use, Asia-Pacific countries can achieve significant cuts in agriculture-related greenhouse gas (GHG) emissions. Various countries have long-standing expertise in non-chemical pest management. Biodiversity-based techniques prevent pest attacks, raise crop yield and boost farm profit. Policy changes, awareness-raising, and farmer education can propel pesticide-free farming

ACKNOWLEDGEMENTS

The development of this policy brief was made possible through a seed-funding grant from FAO RAP to the University of Queensland. FAO RAP equally provided technical support and preparing and editing for publication. The scientific article that was linked to this policy brief (Wyckhuys et al., 2022. Nature Food) also benefited from ideas and writing inputs of Dr. Wei Zhang at the International Food Policy Research Institute (IFPRI) of the Consultative Group of International Agricultural Research (CGIAR). These inputs potentially are also -to a certain extent- reflected in this policy brief. Finally, we also thank FAO, Regional Office, Bangkok for the valuable support.

REFERENCES

Armengot, L., Barbieri, P., Andres, C., Milz, J., & Schneider, M. (2016). Cacao agroforestry systems have higher return on labor compared to full-sun monocultures. *Agron. Sustain. Dev*. 36(4), 1-10.

Bale, J. S., Van Lenteren, J. C., & Bigler, F. (2008). Biological control and sustainable food production. Philosophical Transactions of the Royal Society B: Biol. Sci. 363(1492), 761-776.

Bridge, G., Bulkeley, H., Langley, P., & Van Veelen, B. (2020). Pluralizing and problematizing carbon finance. *Prog. Hum. Geog*. 44(4), 724-742.

Carlson, K. M., Gerber, J. S., Mueller, N. D., Herrero, M., MacDonald, G. K., Brauman, K. A., Havlik, P., O'Connell, C. S., Johnson, J. A., Saatchi, S., & West, P. C. (2017). Greenhouse gas emissions intensity of global croplands. *Nat. Clim. Change*. 7(1), 63-68.

Cook-Patton, S. C., Drever, C.R., Griscom, B.W., Hamrick, K., Hardman, H., Kroeger, T., Pacheco, P., Raghav, S., Stevenson, M., Webb, C. & Yeo, S. (2021). Protect, manage and then restore lands for climate mitigation. *Nat. Clim. Change*. 11(12), 1027-1034.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., & Leip, A.J. N.F. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food*, 2(3), 198-209.

da Consolação Rosado, M., de Araújo, G.J., Pallini, A., & Venzon, M. (2021). Cover crop intercropping increases biological control in coffee crops. *BioContro*l. 160, 104675.

Delaquis, E., de Haan, S., & Wyckhuys. K. A. (2018). On-farm diversity offsets environmental pressures in tropical agro-ecosystems: a synthetic review for cassava-based systems. *Gric. Ecosyst. Environ*. 251, 226-235.

Douglas, M. R. & Tooker, J. F. (2015). Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in US field crops. *Environ Sci Technol*. 49(8), 5088-5097.

Gurr, G. M., Lu, Z., Zheng, X., Xu, H., Zhu, P., Chen, G., Yao, X., Cheng, J., Zhu, Z., Catindig, J. L., & Villareal, S. (2016). Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nat. Plants*, 2(3), 1-4.

Heimpel, G. E., Yang, Y., Hill, J. D., & Ragsdale, D. W. (2013). Environmental consequences of invasive species: greenhouse gas emissions of insecticide use and the role of biological control in reducing emissions. *PLoS One*, 8(8), e72293.

Landis, D. A., Wratten, S. D., & Gurr, G. M. (2000). Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annu. Rev. Entomol*. 45(1), 175-201.

Li, J., Liu, B., Pan, H., Luo, S., Wyckhuys, K. A., Yuan, H., & Lu, Y. (2019). Buckwheat strip crops increase parasitism of *Apolygus lucorum* in cotton. *BioControl*, 64(6), 645-654.

Losey, J. E. & Vaughan, M. (2006). The economic value of ecological services provided by insects. *Bioscience*, 56(4), 311-323.

Mason, P. G. (ed.). (2021). *Biological control: global impacts, challenges and future directions of pest management*. CSIRO Publishing, Clayton, Australia.

Möhring, N., Ingold, K., Kudsk, P., Martin-Laurent, F., Niggli, U., Siegrist, M., Studer, B., Walter, A., & Finger, R. (2020). Pathways for advancing pesticide policies. *Nat. Food*, 1(9), 535-540.

Olkowski, W. & Zhang, A. (1998). *Habitat management for biological control, examples from China*. In: Pickett, C.H., Bugg, R.L. (Eds.), Enhancing biological control: habitat management to promote natural enemies of agricultural pests. University of California Press, Berkeley, 255–270.

Pan, H., Xiu, C., Liu, B., Wyckhuys, K. A., & Lu., Y. (2020). Whorl-stage maize provides a microclimate refuge for predatory ladybeetles. *BioControl*, 142, 104162.

Rosenzweig, C., Mbow, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E. T., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., & Tubiello, F. N. (2020). Climate change responses benefit from a global food system approach. *Nat. Food*, 1(2), 94-97.

Safa, M. & Watts, M.. 2014. *Energy inputs in pest control using pesticides in New Zealand* (Eds. Pimentel, D. & Peshin, R.). Springer.

Schreinemachers, P., Chen, H. P., Nguyen, T. T. L., Buntong, B., Bouapao, L., Gautam, S., Le, N.T., Pinn, T., Vilaysone, P., & Srinivasan, R. (2017). Too much to handle? Pesticide dependence of smallholder vegetable farmers in Southeast AsiaSci. *Total Environ*. 593, 470-477.

Schreinemachers, P., Grovermann, C., Praneetvatakul, S., Heng, P., Nguyen, T.T.L., Buntong, B., Le, N.T., & Pinn, T. (2020). How much is too much? Quantifying pesticide overuse in vegetable production in Southeast Asia. *J. Clean. Prod*. 244, 118738.

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., van der Heijden, M. G., Liebman, M., & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv*. 6(45), 1715.

Tang, F. H., Lenzen, M., McBratney, A., & Maggi, F. (2021). Risk of pesticide pollution at the global scale. *Nat. Geoscience*, 14(4), 206-210.

Tomich, T. P., Brodt, S., Ferris, H., Galt, R., Horwath, W. R., Kebreab, E., Leveau, J. H., Liptzin, D., Lubell, M., Merel, P., & Michelmore, R. (2011). Agroecology: A review from a global-change perspective. *Annu. Rev. Environ. Resour*. 36, 193-222.

Vanbergen, A. J., Aizen, M. A., Cordeau, S., Garibaldi, L. A., Garratt, M. P., Kovács-Hostyánszki, A., Lecuyer, L., Ngo, H. T., Potts, S. G., Settele, J., & Skrimizea, E. (2020). Transformation of agricultural landscapes in the Anthropocene: Nature's contributions to people, agriculture and food security. *Adv. Ecol. Res*. 63, 193-253.

Van den Berg, H. & Jiggins, J. (2007). Investing in farmers-the impacts of farmer field schools in relation to integrated pest management. *World Dev*. 35(4), 663-686.

van Lenteren, J. C., Bolckmans, K., Köhl, J., Ravensberg, W. J. & Urbaneja, A. (2018). Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl*, 63(1), 39-59.

Veres, A., Wyckhuys, K. A., Kiss, J., Tóth, F., Burgio, G., Pons, X., Avilla, C., Vidal, S., Razinger, J., Bazok, R., & Matyjaszczyk, E. (2020). An update of the Worldwide Integrated Assessment (WIA) on systemic pesticides. Part 4: Alternatives in major cropping systems. *Environ Sci Pollut Res*. 27(24), 29867-29899.

Waddington, H., Snilstveit, B., Hombrados, J., Vojtkova, M., Phillips, D., Davies, P., & White, H. (2014). Farmer field schools for improving farming practices and farmer outcomes: A systematic review. *Campbell Syst. Rev*. 10(1), i-335.

Wyckhuys, K. A., Furlong, M. J., Zhang, W., & GC, Y.D. (2022). Carbon benefits of enlisting nature for crop protection. *Nat. Food*, 3(5), 299-301.

Wyckhuys, K.A.G., Heong, K.L., Sanchez-Bayo, F., Bianchi, FJJA, Lundgren, J. G., & Bentley, J. W. (2019). Ecological illiteracy can deepen farmers' pesticide dependency. *Environ. Res. Lett*. 14(9), 093004.

Yang, X., Wyckhuys, K. A., Jia, X., Nieand, F., Wu, K. (2021). Fall armyworm invasion heightens pesticide expenditure among Chinese smallholder farmers. *J. Environ. Manage*. 282, 111949.

Zhu, Y., Chen, H., Fan, J., Wang, Y., Li, Y., Chen, J., Fan, J., Yang, S., Hu, L., Leung, H., & Mew, T. W. (2000). Genetic diversity and disease control in rice. *Nature*, 406(6797), 718-722.