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Harnessing nature-based solutions for smallholder plant health in a changing climate

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Paul A. Egan (SLU) & David Chikoye (IITA), Editors

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Harnessing nature-based solutions for smallholder plant health in a changing climate

Paul A. Egan (ed.)[1], David Chikoye (ed.)[2], Kristina Karlsson Green[1], Manuele Tamò[3], Benjamin Feit[4], P. Lava Kumar[5], Ranajit Bandyopadhyay[5], Ghislain Tepa-Yotto[3], Alejandro Ortega-Beltran[5], May-Guri Sæthre[6], Danny L. Coyne[7], James P. Legg[8], Mattias Jonsson[4]

[1] Swedish University of Agricultural Sciences (SLU), Department of Plant Protection Biology, Alnarp, Sweden
[2] International Institute of Tropical Agriculture (IITA), Lusaka, Zambia
[3] Biorisk Management Facility (BIMAF), International Institute of Tropical Agriculture (IITA), Cotonou, Benin
[4] Swedish University of Agricultural Sciences (SLU), Department of Ecology, Uppsala, Sweden
[5] International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria
[6] Division of Biotechnology and Plant Health, NIBIO, Norwegian Institute of Bioeconomy Research, Norway
[7] International Institute of Tropical Agriculture (IITA), Kasarani, Nairobi, Kenya
[8] International Institute of Tropical Agriculture (IITA), Dar es Salaam, Tanzania

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Summary

The impacts of climate change on resource-poor farmers are especially severe and include increased challenges with food security and food safety. This report explores how linking the frameworks of nature-based solutions, integrated pest management (IPM), and One Health can facilitate the design of climate-resilient plant health systems, with particular benefits for reduced pesticide use and exposure. Climate-smart approaches to IPM are proposed as a means to reduce emerging risks from pest insects, nematodes, weeds, and diseases under climate change. We elaborate the main climate change threats – and adaptation options – for five key nature-based solutions central to IPM: host plant resistance and tolerance, habitat manipulation, biological control, semiochemical control, and the use of biopesticides. We conclude by laying out a road map for 'climate-smart IPM', which outlines the types of support required for practical implementation, such as climate-informed advisory services, information and communication technology, and policy. While emphasis throughout is placed on smallholder production systems – particularly for sub-Saharan Africa – the principles of climate-smart IPM can be considered relevant to crop production generally.

Content

1. Introduction

Farmers suffer substantial crop losses due to damage by pest insects, nematodes, weeds, and diseases (Oerke et al. 2006; Savary et al. 2019), but nowhere are these greater than in the food-insecure regions of low-income countries.

In sub-Saharan Africa and on the Indo-Gangetic Plains, yield loss to pests can be as high as 30–40 % for staple crops such as maize and rice, despite current plant protection measures (Savary et al. 2019). In addition to chronic impacts, acute outbreaks of invasive pests can result in sudden and almost complete crop losses. These events have the power to ruin farmer livelihoods and cause famine more or less overnight. As we write this report, desert locusts are causing havoc in East and southern Africa and are spreading to other regions (Locust watch 2020), whereas the fall armyworm is still advancing its devastating spread over much of Africa and parts of South-East Asia (Nagoshi et al. 2020). Many damaging invasive pathogens and weeds also continue to spread and cause high crop yield losses in low-income countries (Gharde et al. 2018; Kumar et al. 2019), mainly due to the lack of efficient, locally adapted management approaches for smallholder farmers.

Beyond only limiting the quantity of food produced, certain pests also severely affect yield quality and pose a food safety issue to farmers and consumers. It is for instance estimated that 25 % of cereals and nut crops globally are contaminated with mycotoxins produced by crop-infecting fungi. These contaminants result in a wide range of negative impacts on health, trade, income and food security, and in sub-Saharan Africa widespread exposure to aflatoxins in food is of major concern (Xu et al. 2018).

In most parts of the world the main way of managing pest insects, weeds, and diseases continues to involve the application of chemical pesticides – whether applied alone or in combination with more ecological forms of pest control within **'integrated pest management'** (IPM) (Section 2). Unfortunately, in many low and mid-income countries, chemicals that have been deemed unsafe and which are prohibited elsewhere are still commonly used. This is often done under minimal safety precautions (Bunini Manyilizu et al. 2017), which has major implications both for humans and the environment. As a result, acute poisoning and long-term health problems due to pesticide use are still extremely common among agricultural workers and their families in many low-income countries (Kesavachandran et al. 2009; Jørs et al. 2018).

Climate change presents another challenging dimension to the issue of pesticide use and exposure in low and middle-income countries. Contemporary climate change is one of the biggest challenges that humanity has ever faced. It is already resulting in increasing temperatures,

A fall armyworm moth. This species can damage and destroy a wide variety of crops, which causes large economic damage. PHOTO: MATTIAS JONSSON more frequent and severe droughts and floods, and rising sea levels all over the world (IPCC 2014). The impacts on resource-poor smallholder farmers are especially severe (Aryal et al. 2019) and include increased challenges with food security and safety. In particular, pressures from crop pests, disease, and mycotoxin exposure are predicted to increase in many parts of the world, even if such predictions are highly uncertain and likely to be context dependent (Deutsch et al. 2018; Battilani et al. 2018).

Hence addressing the urgent need to reduce pesticide dependency and exposure in food-insecure regions – whilst also supporting farmers to intensify food production under climate change – will call for improved uptake of integrated pest management approaches that are distinctly 'climate smart'. IPM often incorporates the use of several **'nature-based solutions'** for pest control (Section 2) that allow farmers to reduce or avoid the use of chemical pesticides. However, climate change also poses a serious threat to the function of these nature-based solutions. Greater understanding of these threats is needed in order to build adaptive IPM strategies in cooperation with farmers; a critical step towards securing sustainable reductions in pesticide use and food security under climate change.

This report explores how linking the frameworks of nature-based solutions, IPM, and One Health can support the design of more climate-resilient IPM programs for farmers in low- and middle-income countries (Section 2). Any action to ensure climate resilience will first require detailed understanding of the threats to key nature-based solutions (Section 3), which provides a foundation to adapt more climate-smart approaches to IPM (Section 4). Building on these preceding sections, a road map for practical implementation of **'climate-smart IPM'** is laid out, which elaborates support needs across key domains such as advisory services, information and communication technology, and policy (Section 5).

2. Nature-based solutions, IPM, and One Health – action at the intersection

Nature-based solutions and IPM are both widely promoted in the scientific literature and in national and international policies (e.g. Lee et al. 2019; Nesshöver et al. 2017), yet to date only the latter is explicitly elaborated in the context of plant health. Nature-based solutions refer to the use of approaches that are inspired or driven by nature to tackle socio-environmental and safety challenges – for instance in urban greening and disaster-risk reduction initiatives (Nelson et al. 2020). IPM refers to the integrated use of conventional and ecosystem-based practices to control pest insects, weeds, and pathogens, with a particular focus on reducing farmer reliance on chemical pesticides. To ensure adoption by smallholder farmers, it is especially critical to tailor IPM strategies using participatory approaches (Section 5).

Despite their lack of elaboration, the contributions of nature-based solutions to plant health are nonetheless apparent (Figure 1). Five practices that routinely underpin IPM strategies can in fact be considered nature-based solutions:

1. The development and use of **resistant and tolerant crop varieties;**
2. The **biological control** of pests by their natural enemies;
3. **Habitat manipulation**, such as push-pull systems (Box 1), for pest deterrence and weed suppression;
4. The use of **biopesticides** such as plant- and microbially-derived compounds; and
5. Exploitation of **semiochemicals** (i.e., the chemical signals used by pests) for pest monitoring and trapping.

Resistant and tolerant crop varieties are a key nature-based solution for plant health that can reduce farmer reliance on chemical pesticides.

Box 1 – Push-pull pest management in maize and sorghum: a resilient nature-based solution for East African farmers

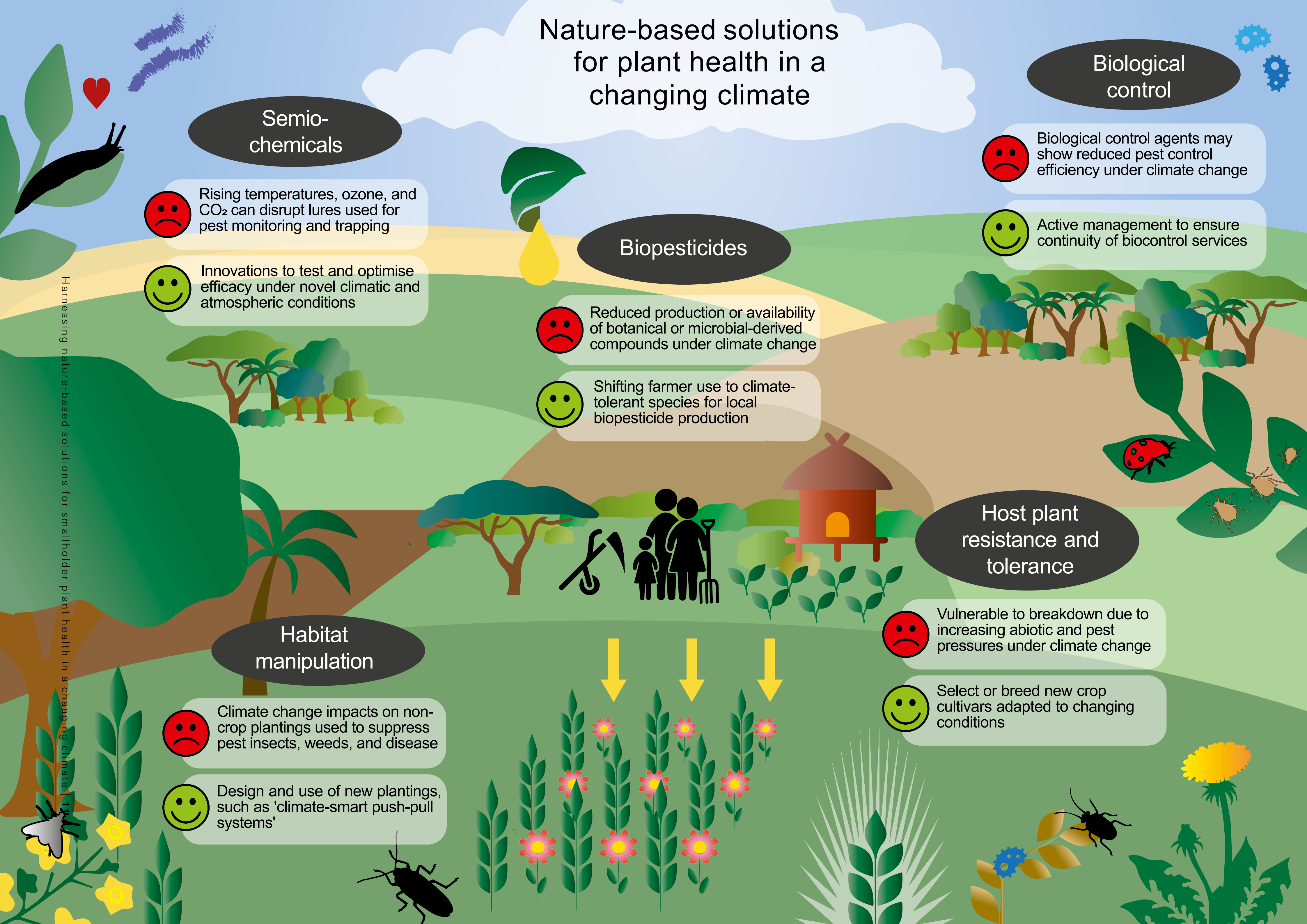
Maize and sorghum are key staple crops for many resource-poor farmers in Africa. These crops are attacked by a range of pests (insects, weeds, and pathogens). A very successful way of managing several of these biotic challenges, while at the same time improving soil fertility, is the push-pull cropping system (e.g. Cook et al. 2007) developed by the International Centre of Insect Physiology and Ecology (icipe) in Kenya, together with Rothamsted Research in the UK. This mixed cropping system was first developed to control stemborer moths by exploiting their chemical interactions with plants already growing locally on the farms. The push component is an intercrop that repels the stemborers and thus pushes them away from the crop, while at the same time attracting certain natural enemies of the pest. The pull component is a plant that attracts the stemborers to a surrounding trap crop.

In the original version, the push-intercrop was the silverleaf desmodium (*Desmodium uncinatum*) and the trap crop was Napier grass (*Pennisetum purpureum*). Later, this system has been adapted to drier conditions into a version called 'climate-smart push-pull' that combines greenleaf desmodium (*Desmodium intortum*) and *Brachiaria grass* (*Brachiaria cv mulato* II). More recently it has been realised that *Desmodium* spp. help to control the devastating parasitic Striga weed by causing suicidal germination of its seeds (Midega et al. 2017), and that it can reduce fall armyworm abundance by over 80 %. Together with improving soil fertility through nitrogen fixation by the intercrop, this results in consistent increases in yield. Due to lowered incidence of grain-damaging insects in push-pull systems, the mycotoxin fumonisin is also reduced in maize (Njeru et al. 2020). Adoption rates of this technique are increasing steadily, and the approach is currently estimated to be benefitting more than two hundred thousand farmers in East Africa (see http://www.push-pull.net/adoption.shtml).

Nature-based solutions can therefore be considered key components of IPM, where their combined use alongside other types of IPM practices (e.g. crop rotation, soil tillage, physical barriers to shield crops – see also Box 2) can contribute towards sustainable reductions in pesticide use and securing food production and food safety.

Within the context of plant health, both nature-based solutions and IPM can furthermore be viewed as operational components of – or contributing factors to – 'One Health'. One Health takes an interdisciplinary perspective towards ensuring the joint health of people, animals, plants, and their shared environment (see example in Box 2), including soil. However, there still remains little recognition of the potential links and synergies between these paradigms, although awareness does appear to be emerging on the need to integrate food safety, food security, and sustainable food production into One Health approaches (e.g., Garcia et al. 2020). Scheme 1 therefore elaborates some of the important intersections between each as they apply to plant health – and in the context of climate change. Greater recognition of these linkages can have important benefits when it comes to policy development and enactment on plant health in low-income countries (Section 5).

Figure 1 (next page). Nature-based solutions for plant health. The most critical threats posed by climate change are highlighted for each, alongside some promising options for adaptation in the form of 'climate-smart' integrated pest management (CS-IPM), which is further elaborated in section 4.
ILLUSTRATION: CAJSA LITHELL


Nature-based solutions for plant health in a changing climate
Semio-chemicals
Rising temperatures, ozone, and CO_2 can disrupt lures used for pest monitoring and trapping
Innovations to test and optimise efficacy under novel climatic and atmospheric conditions
Biopesticides
Reduced production or availability of botanical or microbial-derived compounds under climate change
Shifting farmer use to climate-tolerant species for local biopesticide production
Biological control
Biological control agents may show reduced pest control efficiency under climate change
Active management to ensure continuity of biocontrol services
Habitat manipulation
Climate change impacts on non-crop plantings used to suppress pest insects, weeds, and disease
Design and use of new plantings, such as 'climate-smart push-pull systems'
Host plant resistance and tolerance
Vulnerable to breakdown due to increasing abiotic and pest pressures under climate change
Select or breed new crop cultivars adapted to changing conditions

Complexity →

	Nature-based solutions for plant health	IPM	One Health
Inputs	• Biological control • Habitat manipulation • Host plant resistance and tolerance • Biopesticides • Semiochemicals	Nature-based solutions **plus**: • prioritisation of their optimal combination with each other, and with additional IPM elements (including judicious use of pesticides) • coupled farmer guidance on monitoring, economic decision making, and intervention	IPM **plus** wider focus on vector control, food security/ safety, and pesticide risk reduction for: • farmers • consumers – food contaminants (e.g. aflatoxins, pesticide residues) • animals and biodiversity – especially ecosystem service providers beyond biocontrol agents (e.g. pollinators, nutrient cyclers)
Scale	Mostly plot/field based (exception: biological control may also be managed at landscape scale depending on the target pest)	Plot/field/'farm' but targeting entire cropping systems	Regional level, including human/social dimensions
Impact domain	Mainly to control single pests (exceptions can include habitat manipulation and non-specific/generalist biopesticides and biocontrol agents)	Controlling multiple pests in cropping systems	Human, animal, plant and environmental health
Climate change implications	Both positive and negative potential effects on the ecological processes underpinning nature-based solutions to plant health	Shifts in the most optimal combination of pest control practices, requiring reprioritisation of IPM strategies and communication	Risk of increased pesticide use and exposure owing to altered pest dynamics – e.g. more frequent climate-related outbreaks, plant invasions, and mycotoxin contamination

Scheme 1. Intersectional overlap between the frameworks of nature-based solutions, integrated pest management (IPM), and One Health as they apply to plant health and climate change.

Box 2 – Managing plant health risks to vegetable crops – intersectional action across nature-based solutions, IPM, and One Health

In sub-Saharan Africa, intensive vegetable production in urban and peri-urban areas is the fastest growing agricultural subsector with significant contributions to food security, national incomes, and informal employment opportunities (Godonou et al. 2019). Under pressure from land scarcity and increasing food demands from escalating urban populations, abuse of chemical pesticides has however become the norm for the control of numerous vegetable pest insects (e.g., *Aphis gossypii, Helicoverpa armigera, Plutella xylostella, Tetranychus evansi*) and diseases (Bacterium spp., *Fusarium* spp., *Ralstonia solanacearum*). Field surveys carried out by the International Institute of Tropical Agriculture (IITA) and partners in West Africa (see Godonou et al. 2019) indicated severe health and environmental impacts similar to those that followed agricultural intensification in Asia, where parallel exposure to highly toxic pesticides resulted in deteriorated One Health outcomes for smallholder farmers and agroecosystems. These insecticides in particular degraded indigenous natural enemy populations, thereby creating new pests such as leaf miners and tetranychid mites. In response, IPM strategies were promoted which drew heavily on nature-based solutions (i.e., combined use of biocontrol agents, biopesticides, and crop plant resistance) together with sustainable cultural practices (e.g. adequate crop rotation, intercropping, and incorporation of organic manure). IITA and partners have established strong baseline information on pest diversity, distribution, and importance, as well as the impacts and consequences of pesticide use in intensive vegetable systems. This information should now be used to test and implement additional IPM strategies elsewhere in Africa, for which key actions will include intensive training of farmers and knowledge provision by extension agents.

3. Climate change threats to plant health

A good understanding of the threats posed by climate change is an essential requisite to developing resilient plant health systems based on nature-based solutions (Section 4).

By causing shifts in temperature and precipitation, and by increasing the variability and unpredictability of weather patterns, climate change is altering environmental conditions on a global scale (IPCC 2014). Climate change impacts on crop yields are already evident (Lobell & Field 2007) and are projected to further worsen in response to future changing conditions (Challinor et al. 2014). Changes in pest pressure have already likely contributed to warming-related effects on yield (Lobell & Field 2007), although it still remains poorly understood as to what extent.

In relation to the future impacts of climate change on plant health, there is still little direct evidence available to forecast the long-term consequences, or to guide adaptive responses in the form of 'climate-smart' IPM. However, below we elaborate four facets of plant health that are likely to necessitate a reprioritisation of IPM strategies as climatic change intensifies (see also Figure 1). These relate to how climate change is anticipated to alter:

1. The geographic distribution, abundance, and growth rates of pest species;
2. The crop's own physiological capacity to resist or tolerate damage;
3. The dynamics and effectiveness of biological control agents; and
4. The effectiveness of other important nature-based solutions for plant health, including habitat manipulation, biopesticides, and semiochemical-based control.

i) Pest distribution and biology

As a consequence of climate change, pest pressure is expected to generally increase globally as pests that are already established are likely to develop faster lifecycles and hence more rapid population build-up within a season (Macfadyen et al. 2018). Coupled with this, new species are projected to expand their distribution into previously unsuitable regions (Hellmann et al. 2008; Maiorano et al. 2014; Deutsch et al. 2018; Garett et al. 2016).

A recent study of climate change effects on pest pressure on maize, rice and wheat, for example, predicted additional global pest-related yield losses of 10–25 % per 1.0 °C of mean surface temperature increase, with the largest yield reductions likely to occur in temperate regions

As a consequence of climate change, pest pressure is expected to generally increase globally.
PHOTO: MATTIAS JONSSON

Abiotic stress such as extreme heat, drought, floods, and salt exposure may weaken crops and increase their susceptibility to pest damage.

where current yield levels are highest (Deutsch et al. 2018). In coffee, a major commodity crop that supports the livelihoods of millions of smallholders worldwide, several major pests (i.e., coffee leaf miner, coffee berry borer, and the coffee white stem borer) are predicted to increase their range and damage potential by 2050 owing to altered temperatures and precipitation (see Ziska et al. 2018 and references therein).

When examining the global spread of crop pests and diseases, several root knot nematodes (*Meloidogyne incognita, M. javanica*, and *M. arenaria*) were among the most rapidly spreading of all pests (Bebber et al. 2014). For crop diseases, increased range expansion may be both due to biological factors, such as changes in sporulation and the survival of inoculum, and human activities, such as long-range transport (Prank et al. 2019). Climate change may additionally affect the growth patterns and food safety risk of mycotoxigenic fungi (Cervini et al. 2019).

ii) Crop resistance and tolerance

The potential breakdown of crop resistance and tolerance to pests under climate change has serious consequences for the use of this strategy within IPM (Zhang & Batley 2020). This issue also needs to be seen in the context of increasing abiotic stress (e.g., extreme heat, drought, floods, and salt exposure) which may further weaken crops and increase their susceptibility to pest damage. For insects and pathogens, enhanced growth rates under climate change may also help these organisms overcome hitherto effective defences (Sharma 2014; Elad & Pertot 2014), such as by permitting more effective detoxification abilities (van den Bosch & Welte 2017).

The potential for breakdown in crop resistance and tolerance is unfortunately high, given that these traits are underpinned by a multitude of physiological and genetically controlled mechanisms (e.g., various signalling pathways involved in the biosynthesis of defensive compounds) that are prone to interference. For instance, the combined effects of elevated temperature and CO_2 can impact pest resistance in key staple crops such as cassava (Forbes et al. 2020). Some forms of resistance become inactive above certain temperature thresholds, such as the *Mi* gene in tomatoes against some root knot nematodes (*Meloidogyne* spp.), which becomes ineffective at temperatures above 28°C (Dropkin 1988). Against this backdrop, the cost-benefit ratio of continuing the high level of investment in resistance breeding may become less favourable, in which case prioritisation of other more climate-stable crop protection strategies may be more beneficial.

iii) Biological control

Most modelling studies focus on the direct effects of climate change on pests, and typically overlook the indirect effects modulated by their natural enemies, and how these may also change (Castex et al. 2018; Sun et al. 2020). As a critical nature-based solution for plant health, there is insufficient knowledge on the future climate resilience of biocontrol services – particularly for low-income countries where dependence on natural biocontrol is highest. Furthermore, whether natural enemies of pests will be able to respond to increased pest densities, and maintain effective biocontrol services under future climatic conditions, will depend on their ability to adjust to new conditions. This response will largely hinge on their thermal tolerance (Pörtner & Farrell 2008) and exposure to temperature regimes outside a preferred range, which can severely reduce pest control potential (Huey & Stevenson 1979).

In addition, climate change will also affect the distribution, phenology, and physiology of alternative host plants for insect pests and diseases, which in turn will also affect the population dynamics and efficiency of their related natural enemies. Increased abiotic stress may also risk altering the chemistry of nectar and pollen resources required by natural enemies (Palmer-Young et al. 2019).

iv) Other nature-based solutions

Other nature-based solutions harnessed in IPM that may require adaptive modification under climate change are habitat manipulation and the use of biopesticides and semiochemical-based control. Habitat manipulation typically refers to actions taken to enhance vegetative cover or diversity at farm or landscape scale for cultural or biocontrol benefits (Gurr et al. 2017; Egan et al. 2020). In low-income countries there is usually a higher reliance on natural vegetation rather than the use of managed non-crop plantings (e.g., flower strips), although notable exceptions include companion planting with repellent or trap plants in African 'push-pull systems' (Box 1) and nectar-rich plants in Asian rice monocultures (Bottrell & Schoenly 2018).

Climate change alteration of the cover and composition of natural vegetation, and climatic suitability for native companion plant species, could hence threaten their associated pest suppressive functions. Reduced woody cover in field boundaries may for instance render crop fields more open to vertebrate pest movement (van Vuren and Smallwood 1996; Rao et al. 2015), and provide less habitat for predatory birds (Karp et al. 2013), whereas reduced herbaceous cover will diminish the availability of resources for invertebrate natural enemies – i.e. SNAP (shelter, nectar, alternative prey/hosts, pollen) (Gurr et al. 2017; Schmitz & Barton 2014).

Rising temperatures and atmospheric levels of ozone and CO_2 can also have implications for the production and biological effectiveness of semiochemicals and biopesticides (Blassioli-Moraes et al. 2019). Semiochemicals such as insect pheromones are often used in IPM as lures for pest monitoring, 'attract and kill' strategies, and in mating disruption. While little is known on how climate change may affect insect pheromonal communication, increased pheromone exposure to oxidative gases could impact long-range signalling (Boullis et al. 2016) and thereby efficacy in IPM.

Biopesticides include for instance botanical or microbial-derived toxins and repellents, which can be commercially purchased or produced locally by resource-limited farmers as an economic alternative to chemical pesticides (Srinivasan et al. 2019). However, the production and function of biopesticides may be impaired under changing climatic conditions owing to both pest- and plant-related factors. For plants, changes in climatic suitability can influence where it is possible to grow important pesticidal plant resources (e.g., neem, pyrethrum) (Stevenson et al. 2017), as well as affect the plant's own production of pesticidal compounds (e.g., azadirachtin and pyrethrins, respectively). Rising temperatures may also risk affecting crop root exudate profiles that trigger hatching, attraction, and host location in root pests, such as nematodes (Badri & Vivanco 2009).

4. Climate-smart IPM

Definition and principles

Climate change threatens that hard-won gains in IPM adoption in low-income countries (e.g., see Box 1) will be lost if it provokes a return to high reliance on chemical pesticides. To avert this scenario, it has been proposed that pest management needs to become more climate smart (Heeb et al. 2019; Lu & Elbakidze 2018). 'Climate-smart' integrated pest management (CS-IPM) can be considered a more cross-sectoral approach to pest management that is explicitly informed by (and responsive to) climate change (Figure 1). A CS-IPM approach is thus one that anticipates climate-induced changes in pest pressures, and the efficacy of nature-based solutions for plant health, and in response deploys reprioritised monitoring, forecasting, and management actions (backed by advisory and communication services) to secure crop yields and One Health benefits for people (food security, food safety) and the wider environment (Figure 2).

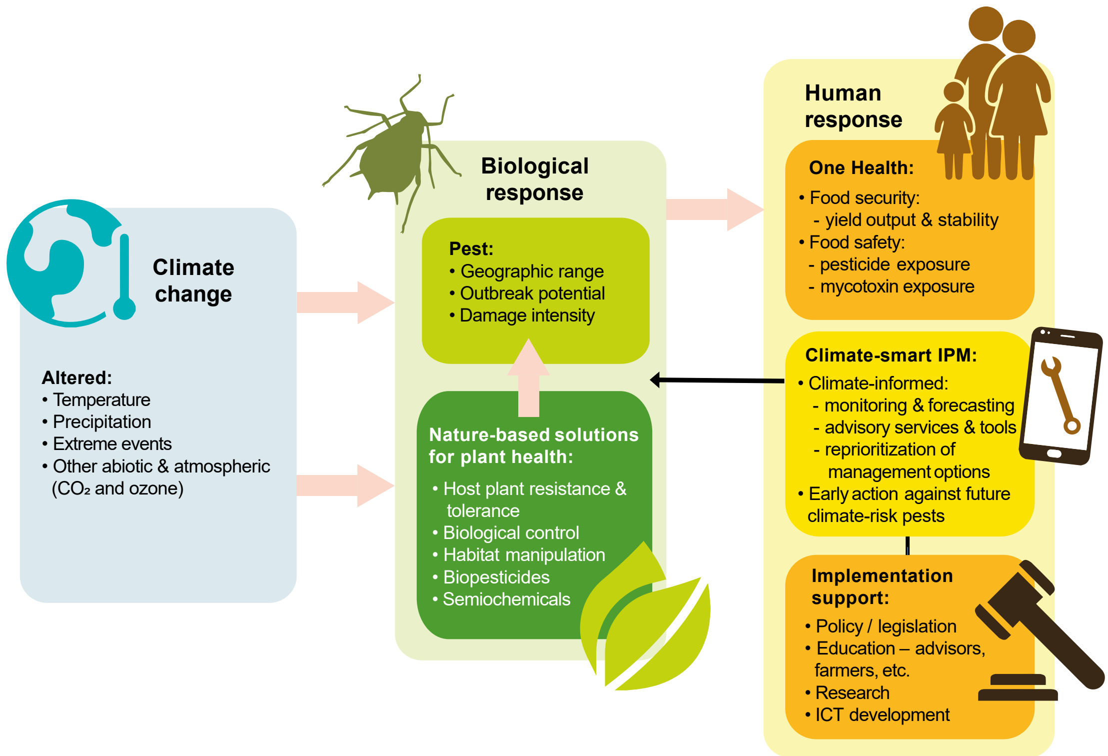


Figure 2. Overview of the potential cascading effects of climate change on pests, nature-based solutions, and One Health outcomes, indicating where 'climate-smart' IPM (CS-IPM) interventions are needed to ensure the resilience of plant health. Climate change will lead to altered abiotic conditions that trigger biological responses by pest insects, diseases, and weeds, but also the nature-based solutions used to control these. Hence, depending on whether pest pressures and nature-based solutions are positively or negatively affected, these effects may either be advantageous or disadvantageous for food safety and security in low-income countries. By adopting CS-IPM principles, farmers and stakeholders can act to mediate the effects of climate change on nature-based solutions underpinning pest management. To develop capacity for CS-IPM actions, different types of implementation supports will crucially be needed.
ILLUSTRATION: CAJSA LITHELL

High-quality, downscaled climate projections and information on pest species' climatic requirements and host plant preference will help controlling new and invasive pests, such as the larvae of the fall armyworm.
PHOTO: MATTIAS JONSSON

For effective implementation of CS-IPM, action must be underpinned by in-depth knowledge of newly emerging climate regimes, how crop pests will respond to these, and the resilience of existing IPM and nature-based solutions for plant health. As such, the principles for successful implementation of CS-IPM are likely to feature:

- **Climate-informed forecasting and monitoring:** Controlling new and invasive pests will require good predictive ability of which pest species may emerge, and which geographic areas and crops are most at risk; i.e., horizon scanning and pest risk assessments for identified and prioritized key pests and their most likely pathways to new areas. Achieving good predictive ability can be enabled by access to high-quality, downscaled climate projections and information on pest species' climatic requirements and host plant preferences. Such modelling approaches have been commonly used for insects such as the invasive fall armyworm, for which the risk of outbreak is actually predicted to decline under climate change (Ramirez-Cabral et al. 2017), but require increased use for plant pathogenic fungi (Ireland & Kriticos, 2019). Identifying where important pests may establish in the future will be vital to informing where monitoring programmes should be initiated in advance. Likewise, it is important to inform phytosanitary personnel about likely pathways for new pests.

- **Climate-informed advisory services and tools:** At the local level, user-friendly and affordable technologies for rapid and reliable reporting of climate-risk species and outbreaks are needed, alongside timely distribution of this information to extension staff, farmers, and decision makers. Weather-based advisory services already exist for many crop pests (Chattopadhyay et al. 2011), although their implementation in low- and middle-income countries remains challenging (see Section 5). At the broader scale, enhanced communication between countries and regions is also needed, so as to be prepared to prevent or quickly act on outbreaks (e.g., Isard et al. 2015). Given that 70 % of future climates are already thought to exist somewhere on earth, adapting a 'climate analogues' approach championed by CGIAR could in this context prove useful (Ramirez-Villegas & Thornton 2015). Expanding this approach to include pests would help to inform which species may prove problematic for a given location, especially if new crops and cropping patterns are to be adapted in response to changing climates (Keatinge et al. 2018).

- **Reprioritisation of IPM options:** Climate change threats to the function of nature-based solutions for plant health (Section 3) and other IPM practices mean that certain strategies which currently work well against established pests may no longer suffice in the future, or function poorly against newly emerging pest species. However, a major determinant of the ability of IPM to provide reliable pest control services under changing conditions is the resilience of current systems to disturbance (Martin et al. 2019). Systems that presently exhibit a high level of climate resilience are likely to maintain their functionality under future conditions, whereas systems of low climate resilience are likely to lose efficacy when exposed to relatively small changes. Practical means to increase the resilience of IPM include incorporating a broader range of pest control practices into IPM strategies, to explicitly introduce new, more resilient practices (see the subsection below), and to enhance diversity of both plants and natural enemies in cropping systems. All three approaches will increase the chances that IPM remains functional, and that farmers are better prepared to make adaptive shifts in management if required.

Combined assessment of crop performance under multiple biotic and abiotic stresses will help to select or breed crop varieties that are robust and well suited to altered climatic conditions. PHOTO: MATTIAS JONSSON

- **Early-action against future climate-risk pests:** A key principle of CS-IPM is to take early preventative control action against new or pre-established pests that are predicted to show greater future distributional spread, outbreak potential, or damage intensity. Enacting this principle will require that all three preceding points are applied together, and that key implementation supports for CS-IPM are put into place (see Section 5 below).

Applying resilient nature-based solutions for climate-smart IPM

Despite the threats that climate change poses to nature-based solutions for plant health (Section 3), in many cases resilience could still be maintained or enhanced if action is taken to adapt IPM strategies (e.g., as suggested by Ziska et al. (2018), using coffee as a case study), or new knowledge is put into place to enable this.

For **host plant resistance and tolerance**, combined assessment of crop performance under multiple biotic and abiotic stresses will help to select or breed crop varieties that are robust and well suited to altered climatic conditions. This prospect was for instance supported by Sun et al. (2018), who identified that enhanced CO_2 levels could upregulate gene activity for aphid resistance in selected genotypes of a model plant. As part of breeding efforts, crop wild relatives (i.e., the wild progenitors of modern crop species) often harbour valuable adaptive traits for use in breeding (Weber et al. 2020; Zhang & Batley 2020). Their use in crop improvement programmes could hence be further expanded as a nature-based solution to adapt crops to climatic- and pest-related stresses.

Increasing host plant resistance to below-ground damage (including by using grafted rootstocks with resistance against root-damaging pests) can additionally increase crop resilience in the face of reducing soil water availability. In particular, the use of resistance against root knot nematodes would provide significant impact across cropping systems in the tropics and sub-tropics, where they are among the most widespread biotic threats (Coyne et al. 2018), especially in coffee-producing countries (Ziska et al. 2018).

To maintain the resilience of **biological control,** both the geographic movement and in-situ survival of natural enemies can be supported. For microbial biocontrol agents in particular, it is suggested that the bioactive ingredients of products should be selected in accordance with various climate change scenarios (Gasperini et al. 2019; Magan & Medina 2020).

Just as it is critical to predict pest species movement under climate change, it will also be important to assess if natural enemies can track pests during geographic range expansion (Castex et al. 2018; Sun et al. 2020). Where this is likely to prove problematic, the translocation of specialist natural enemies could ensure that high-risk pests do not escape into natural enemy free space under climate change and potentially become invasive. Within existing natural enemy communities, resilience to climate change can be ensured via two complementary properties: functional redundancy (diversity of functionally equivalent species (Feit et al. 2019)) and response diversity (diversity in responses to environmental change (Rosenfeld 2002; Feit et al. in preparation)).

Thus, an increased diversity of natural enemies is likely to increase the resilience of biological control to climate change since different species of natural enemies are likely to be adapted to different climatic conditions (Jonsson et al. 2017). A recent study investigating temperature niches of 16 generalist predators in cereal fields in Sweden revealed temperature optima ranging from 15.6 to 34.8°C (Feit et al. in preparation). Undertaking such studies for important cropping systems in low-income countries and managing for high levels of functional redundancy and response diversity (where practical) could thus serve as a type of 'insurance policy' to ensure the continuity of biocontrol services in a changing climate.

As species may spread faster than researchers are able to develop species-specific management, **habitat manipulation** to enhance agroecosystem diversity can serve as a crucial preventive action against emerging pests. Higher levels of biodiversity have been shown to generally, but not always, improve the provision of biocontrol services to crops (Tscharntke et al. 2016), and hence render cropping systems less vulnerable to disturbance and invasions. The above can be achieved by promoting the expansion of natural vegetation in and around farms, but also through the careful selection of climate-tolerant species for use as nectar-rich, repellent, or trap plants, e.g., in 'climate-smart push-pull systems' (Box 1).

Increasing biodiversity in field margins can help prevent emerging pests. PHOTO: MARYSELLAH NELIMA

Climate-smart use of **semiochemicals** and **biopesticides** could play an important role in early-detection monitoring and in combatting emerging pests – such as through the use of pheromone lures in surveillance and 'attract and kill' strategies. Ensuring their efficacy may however require optimisation under novel abiotic and atmospheric conditions. For biopesticides, it could prove beneficial to shift farmer use to more climate-tolerant varieties of key pesticidal plants (Stevenson et al. 2017). In certain instances, altered climatic or atmospheric conditions may even enhance the production of compounds that are inhibitory against pest insects, diseases, or weeds (Forbes et al. 2020; Shah & Smith 2020).

5. Road-map for implementation

Developing farmer capacity to implement climate-smart IPM will require three main foundational supports: i) undertaking participatory research for CS-IPM; ii) improved access to climate-informed advisory services and decision support tools for timely action; and iii) policy development.

Building on the principles of CS-IPM outlined in Section 4, we here highlight important areas to facilitate its implementation and stakeholder involvement and ownership, especially for women farmers. Box 3 in particular summarizes key supporting pillars and stakeholder roles for CS-IPM. While several of these target areas are explicit to climate change challenges, others can be considered useful towards promoting more effective IPM implementation in general.

A number of barriers to IPM adoption have traditionally existed in low- and middle-income countries (Alwang et al. 2019; Parsa et al. 2014). These include a failure to deploy knowledge and technology suited to local conditions, the need to overcome cultural barriers, and lack of integration of indigenous knowledge and traditional practices for managing pests. To better overcome these barriers, Coyne et al. (2019) emphasize a much stronger attention to social considerations, and particularly how gender-related knowledge and competences influence the implementation of IPM approaches. By default, such considerations also extend to the implementation of CS-IPM.

i) Participatory research for CS-IPM

Participatory research with farmers will be essential in all steps taken to develop, improve, and implement climate-smart IPM strategies. Placing farmers' views and practices at the centre of this research – as co-creators of knowledge – will hence ensure that new recommendations are suitable and can be readily adopted. Great opportunities exist to co-develop and improve technology and practical knowledge for CS-IPM. In particular, smallholder farmers and farmer associations can assist with cross-fertilization of ideas spanning plant, animal, and human systems. Such lines of interdisciplinary thinking are critical to realizing the benefits of a One Health approach (Thompson & Brooks-Pollock 2019). Supporting this type of research will however require that national and intergovernmental stakeholders invest in dedicated funding and communication platforms (e.g., Isard et al. 2015; Evans et al. 2020).

ii) Climate-informed advisory services and decision support tools

Successful adoption of new concepts such as CS-IPM are to a large extent dependent on socio-economic considerations (Beddington, 2010). The decision of a farmer to adopt novel technology and pest management tactics may be driven by the perceived cost-benefit ratio of using the new versus the existing technology (Chandler et al. 2011). Agricultural advisors will therefore have an important role to play in demonstrating the economic rationale for climate-smart IPM. As climate-smart IPM is complex and dependent on the combination of several different pest control tactics (that may also need to adaptively shift in response to changing conditions), advisory services should be available to help farmers overcome the challenge of incorporating new tactics into functioning systems, and in deciding whether or not to continue using all previous tactics or abandon some in favour of novel approaches (Chandler et al. 2011).

In addition to advisory services, capacity building for CS-IPM may be further enhanced through farmers associations and the farmer field school concept as promoted by FAO (see e.g., van den Berg et al. 2020). Increasing ecological knowledge among smallholder farmers is cited as a key action to catalyse uptake of nature-based solutions for plant health (Wyckhuys et al. 2019). To build for the future, it will be especially important to increase support for CS-IPM among the next generation of farmers and to improve gender equality to **improve opportunities for women farmers**. Following current best practices (Krupnik et al. 2018), decision-support tools such as mobile phone apps and other data sharing and reporting technology for CS-IPM should ideally be made readily available, user-friendly, and affordable to facilitate common usage. Existing platforms could either be expanded or serve as useful templates – e.g. the 'Integrated Pest Information Platform for Extension and Education' (iPiPe) (Isard et al. 2015).

iii) Policy development

Current policies can be better developed to facilitate farmers, advisors, private sector enterprise, and national and regional agencies to engage with CS-IPM and nature-based solutions for plant health (e.g. Hoeschle-Zeledon et al. 2013). For example, many national policies still largely favour the importation and use of conventional pesticides over that of biopesticides (Chandler et al. 2011), and significant regulatory obstacles still exist regarding the development and use of the latter. However, Coyne et al. (2019) highlight the pivotal role that national and regional regulatory authorities and policy makers can play in helping to streamline the registration of biopesticides and biocontrol products. In particular, fast-track systems could be put in place which allow science-based waivers for certain test requirements (Bandyopadhyay et al. 2016).

Policy development to encourage public-private innovations could also prove to be of significant value. For instance, across sub-Saharan Africa, a recent publicly-funded aflatoxin biocontrol innovation (Aflasafe) has been scaled up via private sector involvement using an

National and regional regulatory authorities and policy makers can play a pivotal role in helping to streamline the registration of biopesticides and products as vital nature-based solutions for climate-smart IPM.

innovative process of making a commercial case for a biopesticide or biocontrol product, licensing the product to carefully selected manufacturers, and technically backstopping them for a limited period (Schreurs et al. 2019; Konlambigue et al. 2020). Beyond biopesticides and biocontrol, identifying opportunities to advance policy for other nature-based solutions could similarly prove of benefit for climate-smart IPM.

As the spread of future pests will occur across nations and even continents, good communication through data sharing and reporting will be necessary between national and international institutions to enhance knowledge-transfer (Avelino et al. 2015; Isard et al. 2015; Evans et al. 2020). To assist with this effort, and with CS-IPM implementation generally, greater recognition of the links between the frameworks of nature-based solutions, IPM, and One Health (Scheme 1) could allow for more harmonised policy development and enactment across borders, which has often proved challenging for low- and middle-income countries (Coyne et al. 2019). This could help to avoid 're-inventing the wheel' (i.e, though duplication of terminology and legislation), permit efficient knowledge transfer and cooperation, and protect functional definitions – e.g. for international certification of sustainably produced products (Partzsch et al. 2019).

Box 3 – Key supporting pillars and stakeholder roles for climate-smart integrated pest management (CS-IPM)

Institutions and researchers
- Risk assessment and horizon scanning to identify potential pest spread under current and future climate scenarios – particularly for current invasive species;
- Regional dissemination of early warning information between institutions and agencies (e.g. from horizon scanning) to enable rapid and coordinated responses;

Advisors, practitioners, and farmers
- Expanded climate-informed advisory services and educational outreach to empower practitioners (especially women farmers) to deploy nature-based solutions within locally adapted CS-IPM strategies;
- Development of farmer decision support tools with increased reach and based on cutting-edge artificial intelligence (AI) and information and communication technology (ICT);

Policy makers
- Regional financing initiatives for research cooperation, capacity building, data sharing, and economic incentives to stimulate CS-IPM development and uptake;
- Improved policies and regulations around the development and registration of biopesticides and biological control products as key nature-based solutions;
- Advocacy and awareness raising to promote CS-IPM as a concept to ensure resilient plant health systems.

6. Conclusions

Crop loss to pests has severe consequences for smallholder farmer livelihoods and food security. Although nature-based solutions provide a foundation for sustainable pest control for many smallholders at present, climate change poses significant threats to their function and is likely to increase pest risks. In response, climate-smart integrated pest management (CS-IPM) can be adapted to ensure the resilience of plant health systems. CS-IPM builds upon an understanding of how nature-based solutions respond to climate change, and links together the frameworks of nature-based solutions, IPM, and One Health.

Putting these principles into action will enable smallholder farmers to achieve better outcomes for plant health and food security in a changing climate, and furthermore provide benefits to biodiversity and human health from reduced pesticide use and exposure. Supporting actions and policy will be essential towards realising these outcomes, and developing capacity for CS-IPM in practice, which will require partnership between a range of stakeholders – from policy makers, governmental agencies, and researchers, to extension services and farmers.

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