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Research article

Perspective article: Food security in tropical Africa through climate-smart plant health management

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ABSTRACT

Each year, Africa loses half of its harvest to pests (insects, pathogens, nematodes, weeds). To offset these losses and improve food security, pest management needs to be revamped urgently. Based on a synthesis of all 58 pest management projects conducted by IITA in its 55-year history, we advocate here for the implementation of the five following key climate-smart interventions, which have been shown to increase yields and decreasing CO_2 outputs compared to the current practices that are largely based on the use of synthetic pesticides: 1. Sanitation at the country's borders and at the field level is the most cost-efficient way to prevent pest damage and losses from exotic pests entering new territories. 2. Good soil management strengthens the crop plant and enhances the effectiveness of all other interventions. 3. Biological control is the quickest and in the long run most cost-effective way to control invading insect pests and weeds. 4. Resistant varieties are often the only way to control already established diseases and are a mainstay control method in combination with other practices. 5. Various bio-pesticides based on viruses, bacteria and fungi against insects have been commercialized or can be produced on-farm; they are to replace synthetic pesticides, which continue to have large negative impacts on the environment and human health. To apply these five practices, new decision-support and climate services tools should be used to empower low-literacy farmers to take timely decisions about pest control and to act as business partners. Meanwhile, all actors in the pest control community should account for their environmental costs, which up to now are born solely by the community, while profits from pesticide sales are pocketed privately. To successfully disseminate these practices across the continent, enhanced and harmonized policy support is required.

1. Every year we lose half the harvest: can we still achieve food security with minimal climate and environmental disturbance?

The two recent agricultural pandemics, the 2016 invasion of the neo-tropical fall armyworm *Spodoptera frugiperda* (FAW) into Africa [1] and the desert locust outbreaks in 2019 [2], revealed a continent-wide, severe lack of preparedness to face such sudden outbreaks and implement sustainable management practices by shifting from costly reactive to more cost-efficient proactive control strategies. Moreover, the implementation of science-based solutions was hindered by political and economic counter-currents, strikingly similar to initial governments responses to COVID-19. Less spectacular – but equally devastating – mostly sedentary arthropod pests, diseases, and weeds continue to severely impact African farm productivity, by some estimates reducing yields globally by 60% [3]. They also prevent commerce through trade barriers or by blocking waterways (as is it the case for floating water weeds).

On top of this comes the expected and observed impacts of climate change on the crops themselves, but just as much on distribution and behavior of pests and diseases, which will further complicate and disrupt crop-pest interactions. In Africa, the impact of climate

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Table 1

Evaluation of all 58 IITA plant health projects 1967–2019 according to different criteria [18]: **Crop**. **Pest group**. **Pest**. **Size of project**: (*1*): small student project, (*2*): several students, more than one university, several donors; (*3*): several international staff, several universities, in several countries; (*4*): scientists from several institutions and donors, up to 5 yrs; (*5*): several institutions, active across continent, with donor consortium, over >5 yrs. **Achievements**: *unpubl*: unpublished data; *publ*: data published in peer-reviewed journal; *proof*: proof of concept under experimental conditions; *test*: tested under farmers' field conditions; *use*: used by Government agencies and NGOs and impact documented; *adapt*: results adapted and extended to other crops and/or continents. **Synthetic chemicals**: contribution to success in %. **Main contributing techniques** (see numbered chapter in text): *cult*: quarantine, phyto-sanitation and use of virus-free planting material (1.) and soil and environmental health management practices (2.); *biocon*: biological control with insects or mites, by introducing agents or favouring existing agents, as well as competitive exclusion (3.); *res*: resistant varieties (4.); *biorational*: biorational techniques involving the use of botanicals, *Bacillus thuringiensis* (*Bt*), fungi, bacteria, viruses and so on (5.); *mixed*: no single technique >50%. **Chapter:** references in chapters of [18]. **Project in bold**: wide-spread use or even adaptation of a plant health intervention to other crops or other continents. **Asterisk** *: Project subjected to socio-economic analysis.

Crop or environment	Pest group	Pest	Size of project	Achieve-ments	Synthetic chemicals %	Other techniques major contribution >50%	Chapters
maize	insect	Fall army worm	5	*publ*	10	*mixed*	4, 7
maize	**fungus**	**Downy mildew**	**3**	***use*** *		***res***	3, 7
maize	insect	Maize stemborers	4	*proof*		*cult*	4, 7, 15
maize	insect	Larger grain borer	5	*proof*		*cult*	7
maize	**fungus**	**Mycotoxins**	**5**	***use*** *		***biorational***	7, 13
maize	**virus**	**Maize viruses**	**5**	***use*** *		***res***	5, 7
cassava	**virus**	**Cassava viruses**	**5**	***use*** *		***res***	5, 6, 15
cassava	**insect**	**Cassava mealybug**	**5**	***adapt*** *		***biocon***	4, 6, 15
cassava	**mite**	**Casssava greenmite**	**5**	***use*** *		***biocon***	4, 6
cassava	insect	*Zonocerus*	2	*test*		*biorational*	6
cassava	bacterium	Cassava bacterial blight	3	*proof*		*res*	3, 6
cassava	fungus	Cassava anthracnose	2	*proof*		*res*	3,6
cassava	insect	ARTS	2	*proof*		*cult*	6
cassava	bacterium	Cassava root diseases	1	*publ*		*cult*	3, 6
cassava	plant	various weeds	2	*unpubl*		*cult*	14
yams	**virus**	**Yams viruses**	**4**	***use***		***res***	8, 12, 15
yams	nematode	Root-knot nematodes	4	*publ*	20	*mixed*	4, 8, 15
yams	fungus	Fungal pathogens	4	*publ*		*cult*	3, 8
cowpea	virus	Cowpea viruses	1	*publ*		*res*	5, 10
cowpea	fungus	Anthracnose	1	*proof*	10	*res*	3, 10
cowpea	fungus	Leaf spot	1	*publ*		*res*	3, 10
cowpea	fungus	Charcoal rot	1	*publ*		*mixed*	3, 10
cowpea	bacterium	*Xanthomonas*	1	*publ*		*res*	3, 10
cowpea	nematode	Root-know nematodes	1	*publ*		*res*	4, 10
cowpea	insect	Cowpea aphids	2	*proof*		*biocon*	10
cowpea	insect	Thrips	3	*proof*	20	*mixed*	10
cowpea	**insect**	***Maruca pod-borer***	**4**	***use***		***biocon***	4, 10
cowpea	insect	*Clavigralla*	2	*proof*	20	*mixed*	10
soybean	fungus	Soybean rust	1	*proof*		*res*	3, 10
soybean	virus	Soybeam viruses	1	*publ*		*res*	5, 10
banana	**virus**	**Banana streak virus**	**3**	***use***		***cult***	5, 9
banana	**virus**	**Banana bunchy top virus**	**3**	***use***		***cult***	5,9
banana	fungus	Fusarium wilt	1	*unpubl*		*cult*	5, 9
banana	fungus	Black Sigatoka	1	*test*	10	*cult*	5, 9, 15
banana	bacterium	Xanthomonas wilt	1	*proof*		*res*	5, 9, 15
banana	**nematode**	**Nematodes**	**2**	***use***		***cult***	4, 9, 15
banana	**insect**	**Banana weevil**	**3**	***use***	10	***cult***	9, 15
plantain	plant	*Chromolaena*	1	*unpubl*	10	*cult*	9, 14
vegetables	**nematode**	***Meloidogyne***	**2**	***use***		***cult***	4, 11
vegetables	bacteria	*Ralstonia*	2	*proof*		*cult*	3, 11
vegetables	**insect**	**Diamond-back moth**	**2**	***use***	10	***biorational***	11
vegetables	insect	Beet web-worm	2	*proof*		*biorational*	11
vegetables	mite	Broad mite	1	*publ*		*biocon*	11
mango	**insect**	**Mango mealybug**	**5**	***adapt****		***biocon***	12
mango	insect	*Batrocera dorsalis*	5	*test*	20	*mixed*	12
mango	**insect**	**Spiralling whitefly**	**1**	***use*** *		***biocon***	12
mango	**insect**	**Papaya mealybug**	**5**	***use*** *		***biocon***	12
cacao	fungus	*Phytophthora megakarya*	2	*proof*	20	*mixed*	12
coconut	mite	Coconut mite	1	*unpubl*		*biocon*	12
cashew	insect	Cashew wood borer	1	*publ*		*cult*	12
Sahel	**insect**	**Locusts**	**5**	***use*** *		***biorational***	6, 12, 13,
Savanna	**plant**	**Speargrass**	**4**	***use*** *	20	***cult***	14
Savanna	**plant**	***Striga***	***5***	***use*** *	5	***cult***	14, 15
Savanna/forest	plant	*Chromolaena*	*1*	*test*	5	*cult*	4, 14
Open water	**plant**	**Water hyacinth**	4	***use****		***biocon***	14

(*continued on next page*)

Table 1 (*continued*)

Crop or environment	Pest group	Pest	Size of project	Achieve-ments	Synthetic chemicals %	Other techniques major contribution >50%	Chapters
Open water	**plant**	**Water fern**	**2**	***use****		***biocon***	14
Open water	**plant**	**Water lettuce**	**3**	***use****		***biocon***	14
Human health	insect	Mosquitos	2	*publ*	20	*cult*	16

* including socio-economic analysis of achievement with reference in the text.

change on ecosystems with shifts of species ranges increasingly leads to adverse impacts on crop production and crop losses from pests and diseases, as well as malnutrition, which affects primarily lower income populations [4].

To increase crop productivity to mitigate these losses, African farmers are mostly left with two options: to expand production to new land at the expense of biodiverse forests and wetlands, important for mitigation of climate change [5]; or to fight biotic stresses with cheap broad-spectrum pesticides [6]. However, indiscriminate use of synthetic pesticides, often obsolete and internationally-banned, has many unintended negative effects on human, animal and environmental health [[7–9]]. Fortunately, the 2020 UN International Year of Plant Health and the 2021 UN Climate Change Conference (COP26) brought a renewed focus on these threats.

This is particularly relevant for tropical Africa, where small-scale subsistence farmers are increasingly challenged by agricultural intensification through higher use of inputs [5]. Consequently, interest in food quality by emerging urban consumers [10] and the protection of the environment with its hidden costs that often affect the most vulnerable [11], have to be taken into account. Most African countries are weak in research and extension capacity, with limited regulatory power, and the negative effects of pesticides on either farmers' and farm workers' health, through inhalation or skin contact, or on consumers' health, through consumption of contaminated food, receive little attention [12]. The 20 countries with highest population growth are all in Africa, and its population is expected to grow to over two billion by 2050. This projected rapid population growth will be among the leading causes of food insecurity and widespread undernourishment across Africa [13].

Seventy percent of Africans will then be living in urban centers, necessitating an enormous expansion of the already strained food value chain [14]. Already now, Africa cannot feed its population, and Africa's current annual food import bill of $35 billion is estimated to rise to $110 billion by 2025 [15], figures that are already outdated, since world food prices have risen sharply, following the war in Ukraine in 2022 [16]. Climate-smart, sustainable and economically profitable plant health approaches are therefore urgently needed to assist the continent with its highly varied agriculture to break out of the spiral of continued natural resource degradation, including loss of biodiversity and soil fertility, while still allowing the necessary intensification of food production [17].

2. New solutions exist, but they require a conducive policy framework for their successful implementation

The International Institute of Tropical Agriculture (IITA) has a unique experience with plant protection in Africa. Its 58 projects executed over 50 years have recently been summarized in a book ([18] with about 1500 references in 16 chapters written by 82 authors). The attribution and relative importance of each descriptor in Table 1 were made by the different project participants according to mutually agreed criteria. The listed research was executed on requests by national agencies. It is focused on key pests whereby large follow-up projects were sometimes financed by different agencies under different titles. Detailed references are listed in the cited chapters. In this paper, we synthesize the lessons learned from this unique experience.

These projects, with different levels of achievement for the benefit of farmers, present the various techniques that contribute to the goal of sustainable agriculture and climate change adaptation and mitigation Our synthesis fits into the two concepts of 'agro-ecology' and 'sustainable food systems'. Agro-ecological practices are defined as those aiming to produce significant amounts of food, while also enhancing ecological processes and ecosystem services. without relying solely on chemical fertilizer, synthetic pesticide applications or technological solutions, such as genetically modified organisms [19]. Sustainable food systems are those that deliver food security and nutrition in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised [20], while regenerative agriculture stresses the sustainability of soil fertility [21].

The first general overview of the 58 projects in Table 1 shows that among the 22 projects with wide-spread use or even adaptation of a plant health intervention to other crops or beyond Africa, biological control (BC) had by far the largest share (40.9% of all successful projects), followed by cultural control measures (31.8%), the use of resistant varieties (13.6%) and biorational measures (13.6%). Synthetic pesticides were used in only 14 projects, and their contribution to the achieved results was rather low (5–20%). All 15 projects subjected to socio-economic analyses demonstrated high profitability of the interventions, with every invested US$ yielding 10-100-fold benefits that accrue directly to the producers.

This is followed by a more detailed review, in which we propose policies and public interventions to implement a set of five science-driven technologies as the blueprint of a new plant health strategy for Africa.

1. **Quarantine at country level and clean planting material** (Table 1 *cult*)**:** Some accidently introduced, exotic organisms have the capacity to become invasive. Horizon scanning and forecasting, followed by early detection for alerting government to impose strict quarantine measures, together with the use of certified planting material and seeds, are the most cost-effective first lines of defense. Once the organisms have established and start to spread, extermination becomes difficult and the costs for controlling them rise

dramatically. The importance of these measures is underscored by the fact that on average every two years three pest species are recorded to have newly established in Africa [22]. Moreover, since the introduction of FAW alone, IITA has identified ten new insect species from outside Africa, including agricultural pest species and their associated natural enemies (G. Goergen, unpublished results).

As an illustration, the banana *Fusarium* wilt TR4, which was initially detected only in one plantation in Mozambique, has since spread throughout the country [23]. This could have been prevented by the application of strict quarantine measures. In Kenya, the spread and incidence of maize lethal necrosis disease was stopped by certified planting material [24]. The impacts of invasive species on biodiversity are well established globally except in Africa [25]. Some of the impacts include decreased abundance and diversity of native species in invaded sites resulting in changes in communities. These impacts have implications for ecosystem services and human well-being. In fact, all invasives that were later controlled by classical biological control (see below), have initially been missed by quarantine measures leading to far greater costs.

Such a precautionary quarantine approach will need to be anchored in regional and national legislative frameworks and coordinated through an interconnected early warning network under a regional/continental organization, building upon current efforts by the Inter-African Phytosanitary Council and the germplasm health unit of the Consultative Group on International Agricultural Research (CGIAR) [26]. Obviously, this will require substantial investments from national governments in creating and/or upgrading quarantine and national plant protection organizations. Similar commitments are needed from regional and continental bodies with enhanced support from the international donor community.

2. **Soil and environmental health management** (Table 1 *cult*)**:** Poor soil management is the root-cause for low crop growth; but Africa's growing populations no longer allow for the long fallows that previously assured continued food production. Poor soil conditions reduce the performance of new crop varieties and, through all trophic levels, affect plant health. Hence, legume-cover, rotation and intercropping, as well as mulching and cover by crop residues reduce the re-establishment of weeds and restore the all-important soil organic matter [3,27]. In its latest climate-smart version [28], the push-pull practice simultaneously reduces maize pests such as FAW and the parasitic weed *Striga*, while increasing maize yields on average threefold; but knowledge gaps in achieving suppressive soils against nematodes and weeds like *Striga* remain. Similarly, Integrated Pest and Pollinator Management (IPPM) [29] combines benefits of planting trees with ecosystem services provided by natural enemies and pollinators, as offered by flowers, nesting sites, and shade trees. Such holistic approaches are leading to more resilient rural landscapes [30,31]. Their realization asks for a radical paradigm change that must be communicated to and implemented by all actors in the farming community and supported by corresponding policies at the highest level [32].
3. **Biological control** (Table 1 *biocon*)**:** In tropical Africa, classical BC has been implemented with success and some projects have even been up-scaled to Asia [33] or South America. Because pest populations build up resistance to pesticides and pest-resistant varieties (in FAW particularly rapidly), the benefits of BC entail not only increased yields, but also reduced labour and environmental costs, and rival those of long-term breeding programs [34]. Economic analysis of BC has consistently shown high returns to investments [35] with economic studies showing spectacular impact against cassava mealybug [36], water hyacinth [37], and mango mealybug [38]. BC also produces less CO_2 than pesticide-based plant protection systems [39]. In view of the huge impact of invasive species and the successful history of classical BC [25,40,41], this should be the first action against invasives. Yet, where long-term follow-up studies are not done, the observed decline of the pest is often attributed to other factors as, e.g., El Niño [42].

BC by indigenous predators and parasitoids and their benefits for increased food production were and still are vastly underreported [43]. Similarly underreported are cases when invading pest species are followed by their parasitoids, which quickly bring the outbreak under control [44].

The ongoing classical BC of FAW in Africa [45] follows similar research on cereal stemborers with various contributions by BC with positive cost-benefit analysis [46]. The FAW project is, however, complicated by the presence of another nine, similar species with their own natural enemies [18]. This highlights the importance of a proper biodiversity assessment considering the entire food-web. Such taxonomic scrutiny allows for synergies between projects, but also avoids negative impact on non-target organisms.

The impact of BC generally depends on a rich, biodiverse landscape [31,47] though many trophic links are often unknown. In order to document and exploit this richness and to warn authorities about the arrival of new invaders, national biodiversity collections need to be created by African scientists and promoted by the African Union [48].

4. **Breeding resistant varieties** (Table 1 *res*)**:** Though time-consuming, breeding for pest resistant varieties is generally one of the most economic approaches to disease control. It is the first defense against plant pathogens such as viruses, e.g., on maize, cassava, and yams. These studies were always accompanied by research on the corresponding vectors, mostly whiteflies for cassava viruses [49] and cicadellids for maize viruses [50]. The genes responsible for resistance against African cassava mosaic and maize streak virus have been successfully introduced in the corresponding varieties across the continent.

For this purpose, plant breeders, facilitated by marker assisted selection, have relied on the genetic diversity in farmers' varieties and gene banks, especially those maintained by the different CGIAR Centers [26].

Still, for some pests and diseases, neither conventional nor molecular breeding approaches led to resistant varieties. To date, the only operational level of host plant resistance against banana *Xanthomonas* wilt was achieved by transforming bananas with a gene from sweet pepper [51]. Similarly, cowpea was transformed with *Bt*-genes for resistance against legume pod borer *Maruca vitrata* [52].

However, these two varieties, classified as genetically modified organisms (GMOs), have so far only been deployed at pilot sites in Africa. Use of GMOs on the continent is mostly prevented because of regulatory barriers at country level, challenges with the logistics of producing and distributing large quantities of planting materials, and – most importantly -political fears regarding access to important export markets in Europe.

New genetic approaches like gene editing, which are not focused on yield only, are being exploited for reactivating genetic traits of wild plants that are modulating interactions between plants, pests and their natural enemies [53]. Since no new genes are introduced, these techniques should allay the fears of agroecologists, who condemn the use of GMOs and see the solution in relying entirely on farmers' techniques that, in their current version, cannot feed the growing populations on the continent. Despite the fact that urban [54] or rural [55] African consumers do not support such moratoria, they were repeatedly prolonged in many African countries, instead of being replaced by clear regulations for the use of novel genomic approaches, best under the auspices of the AU.

5. **How to minimize the negative footprint of synthetic pesticides** (Table 1 *biorational*): Synthetic pesticides are powerful tools for the immediate control of many plant-health threats, providing the farmer with near-instant relief of pest attacks. Yet, pesticide use generates large, difficult to quantify externalities by affecting human, animal and environmental health and tends to lock farmers into a treadmill [56]. Precautionary measures to minimize these effects are, however, mostly ignored. Pesticides are often sold by unskilled resellers who induce farmers to use them as the first line of intervention. Safe use is hampered by the lack of personal protective equipment, which is either not available or not affordable. Hence, the use of synthetic pesticides can be justified only as last resort. Methods for reducing volume and better targeting, like seed-coating or even hand-held disk sprayers for ultra-low volume applications are not generally available, nor are less persistent, more target-specific insecticides.

As alternatives, bio-pesticides or plant-derived products like neem are efficient, ecologically safe, and can be produced locally [57, 58]. Yet, some fungal bio-pesticides, such as Green Muscle™ for efficient locust control [59] or similar products used on vegetable crops [60], are more challenging to produce and need corresponding policy-support and international collaboration.

To enhance the use of bio-pesticides, national, regional and continental policies and guidelines for pesticide registrations need to be reformed to enable a fast-tracking of such products. This would generate an enormous boost for bio-pesticide developers and manufacturers as the costs for the often complicated and lengthy registration procedures are among the greatest economic obstacles for them.

Similarly, the use of herbicides is minimized in locally adapted management programs in the framework of conservation agriculture with its three principles: no-till, permanent soil coverage, and rotation/intercropping [3]. To reduce herbicide-use by agronomic measures is, however, challenging, even more so than reducing persistent insecticides or fungicides.

The successful development of Aflasafe™, which competitively excludes aflatoxin-producing *Aspergillus* [61,62] demonstrates how the development of soil management products by the private sector must affect phytosanitary standards and norms. Moreover, the increasing interest of many actors in the world food system, among them all major food multinationals, in regenerative agriculture with its strong focus on soil health is starting to generate impact in the production systems of important commodities like coffee, cacao and cassava [63].

The main, albeit hidden, problem with the over-use of synthetic pesticides consists in the lack of accountability for environmental costs caused by the disruption of ecosystems services that are provided by natural enemies and pollinators - for free. Currently, the costs of restoring environmental damages together with the long-term burden on human health, are borne by the community, while benefits from the sale of synthetic pesticides are pocketed privately. Corresponding research, regulations and policies, strengthened by tax incentives, are therefore urgently needed. Economic models to calculate those trade-offs and optimize pest management technologies are available [64], but need to be fed with field data to provide realistic recommendations. For the practitioners, development and extension services should engage in better public awareness about the unintended effects of synthetic pesticides and their replacement by more sustainable plant health management practices for food production in a One-Health perspective.

3. Implementation

The implementation of the above recommendations is facilitated by modern ICT tools (including barcodes for taxonomic identification) [18]. Thanks to the wide-spread penetration of smartphones into rural areas, it is now possible to obtain rapid identification of bio-risks by using artificial intelligence and field-based molecular diagnostics. Several smart-phone apps, including Farmer Interface Application [65], Plantix [66] and PlantVillage Nuru [67] have been developed to help farmers with rapid identification of pests. Even low-literacy farmers are thereby empowered to take timely decisions about pest control. Because such IPM is knowledge-intensive, its successful implementation necessitates significant government investments in training a new generation of extension agents. Digital agriculture infrastructures, preferably in collaboration with the private sector, are needed to develop the necessary IT applications [17].

The transformation of African agriculture for the next generation of famers will need to be based on strong linkages to markets and the private sector. Tellingly, interest in Green Muscle™ has been resurrected, following the latest desert locust outbreak, and the private sector is again challenged to produce bio-pesticides. Yet, there is no single private sector for plant health, as traditionally ascribed to multinational agrochemical companies. The private sector starts at village level, where farmers become business partners and the production of biocontrol agents and bio-pesticides becomes a profitable business providing income for youth and women. To better support these endeavors, innovative and sustainable financing mechanisms also need to be developed and implemented.

4. Conclusions

Based on the experiences of the 58 IITA-projects, a revised IPM, tailor-made to specific applications, should enable farmers to implement and take full advantage of the results of plant health research. For this to happen, IPM needs to forge a new identity away from the misused justification for spraying synthetic pesticides. In our opinion, and based on our experiences and the evidence that emanated from our analysis, the five types of interventions proposed here are practical, more sustainable, cost-efficient, produce less CO_2 and assure higher yields, than the practices they are to replace, i.e., they are truly climate-smart providing adaptation to climate change.

Farmers do not read scientific papers, so we need to make sure that development actors and NGOs active in promoting good farming should disseminate key recommendations emanating from our studies, and then provide vital feed-back. These research results also need to be communicated to political authorities for better inclusion in national and regional action plans. We therefore need to translate our evidence into policy briefs and engage government officials and investors for developing and implementing science-based plant health strategies. This would replace today's *ad-hoc* interventions, which often are aimed at relieving symptoms rather than correcting the cause.

Ideally, rural development projects funded by international agencies should consider our actionable points in their overall strategy. If this new paradigm for plant protection in Africa is anchored in a regulatory framework at continental level, it will promote a more equitable, sustainable, environmentally friendly, and economically profitable agriculture, contributing to food security and mitigating climate change in Africa and beyond.

Declarations

Author contribution statement

Peter Neuenschwander, Christian Borgemeister, Hugo De Groote, May-Guri Sæthre, Manuele Tamò: Conceived and designed the experiments, Performed the experiments; analyzed and interpreted the data, Contributed reagents, materials, analysis tools or data, Wrote the paper.

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Declaration of interest's statement.
The authors declare no competing interests.

Additional information

No additional information is available for this paper.

Declaration of competing interest

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] G. Goergen, P.L. Kumar, S.B. Sankung, A. Togola, M. Tamò, First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J E Smith) (Lepidoptera, Noctuidae), a new alien Invasive pest in West and Central Africa, PLoS One 11 (2016), e0165632.
[2] T. Showler, Desert locust control: the effectiveness of proactive interventions and the goal of outbreak preventions, 2019, Amer. Entomol. Fall (2019) 181–191.
[3] R.A. Sikora, E.R. Terry, P.L.G. Vlek, J. Chitja, Transforming Agriculture in Southern Africa Routledge, Taylor and Francis Group, London, U.K, 2020.
[4] IPCC, in: H.O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Eds.), Sixth Assessment Report of the Intergovernmental Panel on Climate Change: Impacts, Adaptation and Vulnerability, Cambridge University Press, Cambridge, UK and New York, USA, 2022, https://doi.org/10.1017/9781009325844.
[5] H.P. Binswanger-Mkhize, S. Savastano, Agricultural intensification: the status in six African countries, Food Pol. 67 (2017) 26–40.
[6] S. Haggblade, A. Diarra, A. Traoré, Regulating agricultural intensification: lessons from West Africa's rapidly growing pesticide markets, Dev. Pol. Rev. 40 (2022), e12545.

[7] M.-G. Sæthre, F. Assogba-Komlan, N.O. Svendsen, B. Holen, I. Godonou, Pesticide residues analysis of three vegetable crops for urban consumers in Benin. Human and environmental consequences of abuse and misuse of synthetic pesticides, Acta Hortic. 1007 (2013) 393–401.

[8] P.C. Jepson, M. Guzy, K. Blaustein, M. Sow, M. Sarr, P. Mineau, S. Kegley, Measuring pesticide ecological and health risks in West African agriculture to establish an enabling environment for sustainable intensification, Philosoph. Trans Royal Soc. B 369 (2014), 20130491, https://doi.org/10.1098/rstb.2013.0491.

[9] A.M. Taiwo, A review of environmental and health effects of organochlorine pesticide residues in Africa, Chemosphere 220 (2019) 1126–1140.

[10] H.A. Osei-Kwasi, A. Laar, F. Zotor, R. Pradeilles, R. Aryeetey, M. Green, P. Griffiths, R. Akparibo, M.N. Wanjohi, E. Rousham, The African urban food environment framework for creating healthy nutrition policy and interventions in urban Africa, PLoS One 16 (2021), e0249621.

[11] R.C. Henry, A. Arneth, M. Jung, S.S. Rabin, M.D. Rounsevell, F. Warren, P. Alexander, Global and regional health and food security under strict conservation scenarios, Nat. Sustain. 5 (2022) 303–310, https://doi.org/10.1038/s41893-021-00844-x.

[12] S. Sarkar, J.D.B. Gil, J. Keeley, N. Möhring, K. Jansen, The Use of Pesticides in Developing Countries and Their Impact on Health and the Right to Food, European Union, 2021. Think Tank European Parliament Study 08-01-2021.

[13] C. Hall, T.P. Dawson, J.I. Macdiarmid, R.B. Matthews, P. Smith, The impact of population growth and climate change on food security in Africa: looking ahead to 2050, Intern. J. Agric. Sustain. 15 (2017) 124–135.

[14] S. Sakho-Jimbira, I. Hathie, The future of agriculture in Sub-Saharan Africa, Southern Voice, Policy Brief 2 (2020) 18.

[15] A. Rahman, A. Shaban, Why Is Africa Importing $35bn in Food Annually? AfDB Boss Asks, AfricaNews, 2017. Last updated: 21/04/2017.

[16] T. Lang, M. McKee, The reinvasion of Ukraine threatens global food supplies, BMJ 376 (2022) o676.

[17] M. Tamò, I. Glitho, G. Tepa-Yotto, R. Muniappan, How does IPM 3.0 look like (and why do we need it in Africa)? Current Opinion in Insect Science 53 (2022), 100961 https://doi.org/10.1016/j.cois.2022.100961.

[18] P. Neuenschwander, M. Tamò, Critical Issues in Plant Health: 50 Years of Research in African Agriculture, Burleigh Dodds, Philadelphia, USA, 2019.(a)Chapter 3: Kumar P.L., Legg J.P., Ayodele M., Mahuku G., Ortega-Beltran A., Bandyopadhyay R. Disease Surveillance, Diagnostics and Germplasm Health in Crop Protection in Sub-saharan Africa. Pp. 41-73.

(b)Chapter 4: Goergen G., Neuenschwander P., Coyne D. Conserving and Exploiting Biodiversity in Crop Cultivation in Sub-saharan Africa. Pp. 75-94.

(c)Chapter 5: Legg J., Kumar P.L., Mahuku G., Wosula E., Stavolone L., Terry E., Bosque-Pérez N. Viruses Affecting African Crops and Their Vectors. Pp.95-135.

(d)Chapter 6: Toko M., Neuenschwander P., Yaninek J. S., Ortega-Betran A., Fanou A., Zinsou V., Wydra K., Hanna R., Fotso A., Douro-Kpindou O.K. Identifying and Managing Plant Health Risks for Key African Crops: Cassava. Pp.139-171.

(e)Chapter 7: Bandyopadhyay R., Cardwell K.F., Ortega-Beltran A., Schulthess F., Meikle W., Sétamou M., Cotty P.J. Identifying and Managing Plant Health Risks for Key African Crops: Maize. Pp. 173-212.

(f)Chapter 8: Mignouna B.D., Kumar P.L., Coyne D., Bandyopadhyay R., Ortega-Beltran A., Bhattacharjee R., De Koeyer D. Identifying and Managing Plant Health Risks for Key African Crops: Yams, Taro and Cocoyam. Pp. 213-228.

(g)Chapter 9: Hauser S., Gold C., Pasberg-Gauhl C., Gauhl F., Akello J., Jacobsen K., Norgrove L., Coyne D., Kumar L., Mahuku G., Kaushal M., Nakato V., Tripathi L., Tripathi J. Identifying and Managing Plant Health Risks for Key African Crops: Banana and Plantain. Pp. 229-258.

(h)Chapter 10: Tamò M., Afouda L., Bandyopadhyay R., Bottenberg H., Cortada-Gonzales L., Murithi H., Ortega-Beltran A., Pittendrigh B., Sikirou R., Togola A., Wydra K.D. Identifying and Managing Plant Health Risks for Key African Crops: Legumes. Pp. 259-294.

(i)Chapter 11: Godonou I., Sæthre, M.-G., Tepa-Yotto G., Gnanvossou D., Douro-Kpindou O.K., Coyne D. Identifying and Managing Plant Health Risks for Key African Crops: Vegetables. Pp. 295-315.

(j)Chapter 12: Neuenschwander P., Gnanvossou D., Hauser S., Goergen G., Hanna R., Norgrove L., Negloh K., Agboton C. Identifying and Managing Plant Health Risks for Key African Crops: Fruit and Other Tree Crops. Pp.317-342.

(k)Chapter 13: Schreurs F., Bandyopadhyay R., Kooyman C., Ortega-Beltran A., Akande A., Konlambigue M, Van den Bosch N. Commercial Products Promoting Plant Health in African Agriculture. Pp. 345-363.

(l)Chapter 14: Chikoye D., Ekeleme F., Hauser S., Menkir A., Kamara A.Y., Neuenschwander P., Ajuonu O., Ajeigbe H.A. Weeds Affecting Field Crops and Water Bodies in Africa. Pp. 365-396.

(m)Chapter 15: Coyne D., Abberton M., Adetonah S., Ayodele M., Cortada L. Gbaguidi B., Hauser S., Kumar L., Neuenschwander P., Schut M., Tamò M., Togola A. What Makes Integrated Pest Management (IPM) Work in Sub-saharan Africa. Pp. 397-412.

(n)Chapter 16: Neuenschwander P., Tamò M. Sæthre M.-G. Improving Plant Health in Sub-Saharan Africa: Conclusions and Future Challenges. Pp. 415-456.

[19] FAO, The 10 Elements of Agroecology: Guiding the Transition to Sustainable Food and Agricultural Systems, FAO, Rome, 2018.

[20] H. Nguyen, Sustainable Food Systems: Concept and Framework, FAO, Rome, Italy, 2018.

[21] K.E. Giller, R. Hijbeek, J.A. Andersson, J. Sumberg, Regenerative agriculture: an agronomic perspective, Outlook Agric. 50 (2021) 13–25, https://doi.org/10.1177/00300727021998063.

[22] J.K. Waage, J.W. Woodhall, S.J. Bishop, J.J. Smith, D.R. Jones, N.J. Spence, Patterns of plant pest introductions in Europe and Africa, Agric. Syst. 99 (2009) 1–5.

[23] D. Butler, Fungus threatens top banana, Nature 504 (2013) 195–196.

[24] H. De Groote, B.G. Munyua, S. Palmas, L.M. Suresh, A.Y. Bruce, S. Kimenju, Using panel community surveys to track the impact of crop pests over time and space – the case of maize lethal necrosis (MLN) disease in Kenya from 2013 to 2018, Plant Dis. 105 (2021) 1259–1271.

[25] S. Ekesi, R. Day, M.-G. Sæthre, S. Subramanian, I. Rwomushana, S. Fonkou, F. Khamis, K. Akutse (Eds.), Strategy for Managing Invasive Species in Africa 2021-2030, International Centre of Insect Physiology and Ecology (Icipe), CABI, IITA, AU, 2020.

[26] M. Smale, N. Jamora, Valuing genebanks, Food Secur. 12 (2020) 905–918.

[27] H. Mutsaers, D. Coyne, S. Hauser, J. Huising, A. Kamara, G. Nziguheba, P. Pypers, G. Taulya, P. van Asten, B. Vanlauwe, Soil and Fertility Management Research in Sub-saharan Africa. Fifty Years of Shifting Visions and Chequered Achievements, Taylor and Francis, London, U.K, 2017.

[28] D. Cheruiyot, F. Chidawanyika, C.A.O. Midega, J.O. Pittchar, J.A. Pickett, Z.R. Khan, Field evaluation of a new third generation push-pull technology for control of striga weed, stemborers, and fall armyworm in western Kenya, Exp. Agric. 2022 (2022) 1–15, https://doi.org/10.1017/S0014479721000260.

[29] I. Merle, J. Hipólito, F. Requier, Towards integrated pest and pollinator management in tropical crops, Current Opinion in Insect Science 50 (2022), 100866.

[30] S. Kuyah, I. Öborn, M. Jonsson, A.S. Dahlin, E. Barrios, C. Muthuri, A. Malmer, E.J. Nyaga, C. Magaju, S. Namirembe, Y. Nyberg, F.L. Sinclair, Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa, Intern. J. Biodiv. Sci. Ecosyst. Serv. Manage. (2016), https://doi.org/10.1080/21513732.121417.

[31] C. Kremen, A.M. Merenlender, Landscapes that work for biodiversity and people, Science 362 (2018) 6412, https://doi.org/10.1126/science.aau6020, eaau6020.

[32] T.S. Jayne, P.A. Sanchez, Agricultural productivity must improve in sub-Saharan Africa. The region must pivot from area expansion to increasing crop yields on existing farmland, Science 372 (2021) 1045–1047.

[33] K.A.G. Wyckhuys, P. Wongtiem, A. Rauf, A. Thancharoen, G.E. Heimpel, N.T.T. Le, M.Z. Fanani, G.M. Gurr, J.G. Lundgren, D.D. Burra, L.K. Palao, G. Hyman, I. Graziosi, V.X. Le, M.J.W. Cock, T. Tscharntke, S.D. Wratten, L.V. Nguyen, M. You, Y. Lu, J.W. Ketelaar, G. Goergen, P. Neuenschwander, Continental-scale suppression of an invasive pest by a host-specific parasitoid underlines both environmental and economic benefits of arthropod biological control, PeerJ 6 (2018), e5796.

[34] P. Neuenschwander, Harnessing nature in Africa, Nature 432 (2004) 801–802.

[35] B.W. van Wilgen, S. Raghu, A.W. Sheppard, U. Schaffner, Quantifying the social and economic benefits of the biological control of invasive alien plants in natural ecosystems, Current Opinion in Insect Science 38 (2020) 1–5.

[36] J. Zeddies, R.P. Schaab, P. Neuenschwander, H.R. Herren, Economics of biological control of cassava mealybug in Africa, Agric. Econ. 24 (2001) 209–219.

[37] H. De Groote, O. Ajuonu, S. Attignon, R. Djessou, P. Neuenschwander, Economic impact of biological control of water hyacinth in southern Benin, Ecol. Econ. 45 (2003) 105–117.

[38] A. Bokonon-Ganta, H. De Groote, P. Neuenschwander, Socio-economic impact of biological control of mango mealybug in Benin, Agricult., Ecosyst. Environ. 93 (2002) 367–378.

[39] K.A.G. Wyckhuys, M.J. Furlong, W. Zhang, D.G.C. Yubak, Carbon benefits of enlisting nature for crop protection, Nature Food (2022), https://doi.org/10.1038/s43016-022-00510-1 published 5 May 2022.

[40] R. Eschen, T. Beale, J.M. Bonnin, K.L. Constantine, S. Duah, E.A. Finch, F. Makale, W. Nunda, A. Ogunmo, Towards estimating the economic cost of invasive alien species to African crop, CABI Agriculture and Bioscience 2 (2021) 1–18.

[41] C.F. Pratt, K.L. Constantine, S.T. Murphy, Economic impacts of invasive alien species on African smallholder livelihoods, Global Food Secur. 14 (2017) 31–37.

[42] J.R.U. Wilson, O. Ajuonu, T.D. Center, M.P. Hill, M.H. Julien, F. Katagira, P. Neuenschwander, S.W. Njoka, J. Ogwang, R.H. Reeder, T. Van, The decline of water hyacinth on Lake Victoria was due to biological control by *Neochetina* spp, Aquat. Bot. 87 (2007) 90–93.

[43] P. Neuenschwander, S.T. Murphy, E.V. Coly, Introduction of exotic parasitic wasps for the control of *Liriomyza trifolii* (Dipt., Agromyzidae) in Senegal, Trop. Pest. Manage. 33 (1987) 290–297.

[44] Y. d'Almeida, J.A. Lys, P. Neuenschwander, O. Ajuonu, Impact of two accidently introduced *Encarsia* species (Hymenoptera: Aphelinidae) and other biotic and abiotic factors on the spiralling whitefly *Aleurodicus dispersus* Russel) Homoptera: Aleyrodidae), in Benin, West Africa, Biocontrol Sci. Technol. 8 (1998) 163–173.

[45] L.K. Agboyi, G. Goergen, P. Beseh, S.A. Mensah, V.A. Clottey, R. Glikpo, A. Buddie, G. Cafà, L. Offord, R. Day, I. Rwomushana, M. Kenis, Parasitoid complex of fall armyworm, *Spodoptera frugiperda*, in Ghana and Benin, Insects 11 (2020) 68, https://doi.org/10.3390/insects1102006.

[46] A.K. Kipkoech, F. Schulthess, W.K. Yabann, H.K. Maritim, D. Mithoefer, Biological control of cereal stemborers in Kenya: a cost benefit approach, Ann. Soc. Entomol. Fr. 42 (2006) 519–528.

[47] E.W. Evans, Biodiversity, ecosystem functioning, and classical biological control, Appl. Entomol. Zool. 51 (2016) 173–184.

[48] Post-2020 global biodiversity framework. https://www.iucn.org/theme/global-policy/our-work/convention-biological-diversity-cbd/post-2020-global-biodiversity-framework.

[49] J.P. Legg, P. Lava Kumar, T. Makeshkumar, M. Ferguson, E. Kanju, P. Ntawuruhunga, L. Tripathi, W. Cuellar, Cassava virus diseases: biology, epidemiology and management, Adv. Virus Res. 91 (2015) 85–142.

[50] N.A. Bosque-Pérez, Eight decades of maize streak virus research, Virus Res. 71 (2000) 107–121.

[51] L. Tripathi, V.O. Ntui, J.N. Tripathi, CRISPR/Cas9-based genome editing of banana for disease resistance, Curr. Opin. Plant Biol. 56 (2020) 118–126.

[52] P.C. Addae, M.F. Ishiyaku, J.-B. Tignegre, M.N. Ba, J.B. Bationo, I.D.K. Atokple, M. Abudulai, C.L. Dabiré-Binso, F. Traore, M. Saba, M.L. Umar, G.A. Adazebra, F.N. Onyekachi, M.A. Nemeth, J.E. Huesing, L.R. Beach, T.J. V Higgins, R.L. Hellmich, B.R. Pittendrigh, Efficacy of a cry1Ab gene for control of *Maruca vitrata* (Lepidoptera: Crambidae) in cowpea (Fabales: Fabaceae), J. Econ. Entomol. 113 (2020) 974–979.

[53] J.A. Stenberg, M. Heil, I. Åhman, C. Björkman, Optimizing crops for biocontrol of pests and disease, Trends Plant Sci. 20 (2015) 698, https://doi.org/10.1016/j.tplants.2015.08.007.

[54] S.C. Kimenju, H. De Groote, Consumers' willingness to pay for genetically modified food in Kenya, Agric. Econ. 38 (2008) 35–46.

[55] H. De Groote, S.C. Kimenju, F. Kete, O. Ngigi, Z.M. Gitonga, But what do rural consumers in Africa think about GM food? AgBioforum 19 (2016) 54–65.

[56] C. Wilson, C. Tisdell, Why farmers continue to use pesticides despite environmental, health and sustainability costs, Ecol. Econom. 39 (2001) 449–462.

[57] P. Anjarwalla, S. Belmain, P. Sola, R. Jamnadass, P. Stevenson, Handbook on Pesticidal Plants, World Agroforestry Centre (ICRAF), Nairobi, Kenya, 2016.

[58] M.B. Isman, Bridging the gap: moving botanical insecticides from the laboratory to the farm, Ind. Crop. Prod. 110 (2017) 10–14.

[59] C. Lomer, R. Bateman, D. Johnson, J. Langewald, M. Thomas, Biological control of locusts and grasshoppers, Annu. Rev. Entomol. 46 (2001) 667–702.

[60] O. Coulibaly, A.J. Cherry, T. Nouhoheflin, C.C. Aitchedji, R. Al-Hassan, Vegetable producer perceptions and willingness to pay for biopesticides, J. Veg. Sci. 12 (3) (2007) 2742, https://doi.org/10.1300/J484v12n03_04.

[61] R. Bandyopadhyay, A. Ortega-Beltran, A. Akande, C. Mutegi, J. Atehnkeng, L. Kaptoge, A.L. Senghor, B.N. Adhikari, P.J. Cotty, Biological control of aflatoxins in Africa: current status and potential challenges in the face of climate change, World Mycotoxin J. 9 (2016) 771–789.

[62] A. Ortega-Beltran, R. Bandyopadhyay, Contributions of integrated aflatoxin management strategies to achieve the sustainable development goals in various African countries, Global Food Secur. 30 (2021), 100559.

[63] Rainforest Alliance, White Paper. Regenerative Coffee Scorecard (2022), pp. 1–19, https://www.rainforest-alliance.org/resource-item/regenerative-coffee-scorecard/.

[64] G. Norton, J. Alwang, M. Kassie, R. Muniappan, Economic Impacts of Integrated Pest Management Practices in Developing Countries. The Economics of Integrated Pest Management of Insects, CABI Publishing, Boston, MA, 2019, pp. 140–154.

[65] G.T. Tepa-Yotto, J.K. Winsou, B.T.A. Dahoueto, M. Tamò, Assessing new scouting approaches for field sampling of *Spodoptera frugiperda* and its parasitoids, in: Proceedings of the 1st International Electronic Conference on Entomology, 2021, pp. 1–8.

[66] Plantix, 2023. https://plantix.net/en/.

[67] PlantVillage Nuru, 2023. https://www.echocommunity.org/en/resources/e2fa32cb-9089-4976-b3f1-92613e67216e.