Chapter 16

Improving plant health in sub-Saharan Africa: conclusions and future challenges

Peter Neuenschwander *and* **Manuele Tamò**, *International Institute of Tropical Agriculture (IITA), Benin; and* **May-Guri Sæthre**, *International Institute of Tropical Agriculture (IITA), Nigeria (corresponding author: p.neuenschwander@cgiar.org)*

1 Introduction

IITA has experienced tremendous growth since its establishment 50 years ago and especially after 2012 when staff and budget increased three-fold in about 5 years and the institute's tagline was revised from *'Research to Nourish Africa'* to *'Transforming African Agriculture'* with the corresponding changes in perspective. When IITA received the 2018 Africa Food Prize the Director General noted that

> 'A shift is under way from agriculture being seen as a series of commodities alone, toward being seen as a whole ecosystem that has people at its centre. And that by creating job opportunities for rural youth and improving livelihoods, we can ensure food security and nutrition for Africans, and provide a powerful antidote to threats posed by political instability and extremism in the continent' (https://www.africafoodprize.org/2018-africa-food-prize-awarded/)

Africa's problems indeed are enormous. Because its population, estimated at 650 million in 1990, is projected to reach 1.5 billion people by 2025, food demand will more than double within a time frame of less than four decades.

http://dx.doi.org/10.19103/AS.2018.0043.17
Published by Burleigh Dodds Science Publishing Limited, 2019.

The key challenge therefore is to increase agricultural production sustainably by preserving biodiversity and reducing the pressure on ecosystems and natural resources.

IITA grew from a few dozen internationally employed staff in 1967 with a budget of about US$2.5 million p.a. to 224 scientists in 2018 and a mostly project-based budget of over US$100 million p.a. Yet, the number of staff of the entire CGIAR with its 15 institutes across the world only roughly equals the one of corresponding French institutions and is dwarfed by Brazil and India with their national agricultural research institutions with thousands of scientists. Despite of its modest size, IITA is the biggest coordinating research institution within its mandate area of tropical Africa. It is now represented by its own stations in 16 African countries, including those where IITA is hosted by other institutions (Fig. 1).

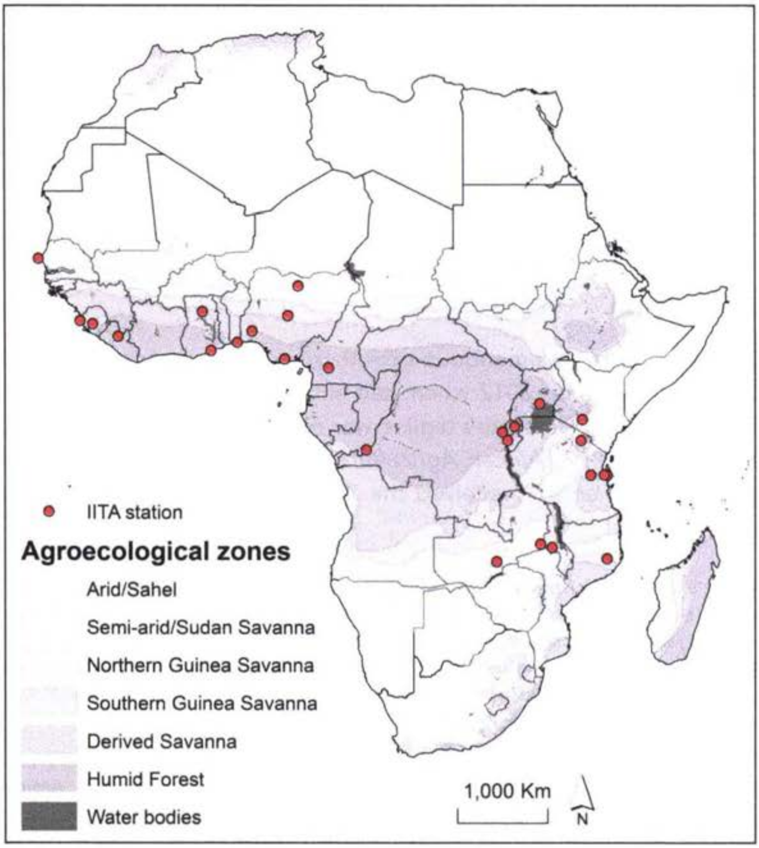

Figure 1 Agroecological zones of Africa with IITA stations as dots.

IITA research to transform Africa puts it on a knife's edge between the activities of big implementing non-government agencies and universities - or in the position of Louis Pasteur in the Pasteur's quadrant (Stokes, 1997). On the one hand, scientific research aims not only to describe but to understand mechanisms (though not all scientists are equally interested in this aspect); on the other hand, the institute implements and documents how its results are being adopted and adapted in order to increase production, sustainability and the well-being of farmers. In the early days, confirming yield increases was the main goal. Today, ideally, we aim to achieve and document higher income and well-being, but also question how this is achieved, with the understanding that this is the only way science can advance. In order to find a holistic solution for all stakeholders, poor versus rich, women and youth, we also address environmental and ecological challenges in close collaboration with our first clients, the various national programmes.

Today, we face increased pressure from donors to stress 'transformation', that is implementation of results. Instant successes at farm level within shortest time periods are thereby expected. Yet, research means that not everything is already known, means accepting failures and accepting also negative results. This requires much patience and confidence by all involved. With the present book on plant health research for development (R4D) we sketch the history and problems in African agriculture (Chapter 2) and pause for a moment in the relentless year-to-year hunting for funds that often makes it difficult to keep the larger and long-term view. The aim is to consolidate and extend the successes of the past 50 years into the future. The cited chapters are listed at the end of the chapter in the section 'Where to look for further information'.

2 The views of IITA clients and peers

In a first step, we asked former collaborators for their opinion about IITA in order to listen to their advice and complaints (Chapter 1). Generally, there seems to be good agreement between requests by national institutions, universities and donors, on the one hand, and IITA's output, on the other hand. In fact, often these requests had already been discussed with our colleagues in the national programmes even before they surfaced as official demands.

A special case is the CGIAR System-wide Program for Integrated Pest Management (SP-IPM), which was very well accepted in Africa, but less so on other continents. It could have served as a model for the CGIAR Research Programmes (CRPs), but was dismissed by donors - in our view a missed chance. A list of CGIAR Research Programs in which IITA is involved is provided in Table 1.

Generally, a holistic IPM approach, coupled with robust phytosanitary arrangements, is given importance by our interviewees. One dissenting voice,

Table 1 CGIAR Research Programs in which IITA is involved

CGIAR Research Program on Climate Change, Agriculture and Food Security	CCAFS generates evidence and supports adoption of climate-smart agricultural policies, practices and services that alleviate poverty, increase gender equity and support sustainable landscapes. CCAFS also plays an integrating role across all of the CRPs.
CGIAR Research Program on Agriculture for Nutrition and Health	A4NH is built on the notion that agriculture can do much more than reduce hunger and poverty - it has an enormous potential to significantly improve the nutrition and health of people around the world. The links between nutrition and climate change are a focus area.
CGIAR Research Program on Policies, Institutions, and Markets	PIM is an action-oriented research to provide support for policies that help poor farmers, both men and women; improve their lives; produce nutritious and affordable foods; and protect the soil, water and biodiversity in rural landscapes.
CGIAR Research Program on Grain Legumes and Dryland Cereals	GLDC aims to increase the productivity, profitability, resilience and marketability of critical and nutritious grain legumes and cereals within the semi-arid and sub-humid dryland agro-ecologies of sub-Saharan Africa and South Asia. In these agro-ecologies poverty, malnutrition, climate change and soil degradation are among the most acute globally.
CGIAR Research Program on Maize	MAIZE is an international collaboration between more than 300 partners that seeks to mobilize global resources in maize research and development to achieve a greater strategic impact on maize-based farming systems in Africa, South Asia and Latin America.
CGIAR Research Program on Roots, Tubers and Bananas	RTB is working globally to harness the untapped potential of those crops in order to improve food security, nutrition, income, climate change resilience and gender equity of smallholders.
CGIAR Genebank Platform	Development of trait-based subsets for climate resilience, conservation and characterization of diversity for both staple and underutilized crops for future climate options.
CGIAR Platform for Big Data in Agriculture	Agriculture to harness the capabilities of big data to accelerate and enhance the impact of international agricultural research.

however, complains about too little reliance on systems models, too weak a fight for organic agriculture (without mineral fertilizers, synthetic pesticides, or GMOs) and requests a total change in IITA's approach to plant health management. This viewpoint will challenge us throughout this chapter. All colleagues stressed the importance of partnerships, which in the end will have an equal if not higher impact than the direct research results. Capacity building must therefore be considered as one of the most important contributions IITA has made.

3 Comparing various IITA projects and their impact

IITA works on demand by the national programmes, but is also heavily influenced by donor requests, which have become ever more detailed. Today, IITA has become a project-based institute, which differs radically from the prevailing reliance on core funding during the first half of its existence. Therefore our analysis follows the fate of projects (and their follow-ups) (Table 2).

Comparing projects with different actors, in different areas and at different times, against different targets, is like comparing 'apples and oranges'. A total of 58 targets that were combatted through sometimes consecutively funded projects or continuously through core funding (up to about 2017) are presented in Table 2 and arranged according to crop plant or environment, pest group and target pest. In order to estimate the importance that IITA gave these projects we characterized them by a confounded criterion from (1) to (5), taking into account the numbers of scientists, collaborating institutions, approximate years of duration, countries where the project had activities and number of donors involved. Evidently not all projects fell clearly into one category and occasionally one of the defining criteria was not met. Achievements were ranked from type of publication to proof of concept to use and adaptation of the results. The contribution of different techniques to the desired project outcome was roughly estimated, namely for (1) synthetic chemicals; (2) so-called biorational techniques involving the use of botanicals, *Bacillus thuringiensis* (Bt), fungi, viruses and so on; (3) biological control with insects or mites, by introducing agents or favouring existing agents, as well as competitive exclusion; (4) resistant varieties; and (5) cultural practices including phyto-sanitation and use of virus-free planting material. Projects were characterized according to which of these techniques contributed to more than half of the impact. Where no technique contributed more than half, the project was labelled as 'mixed'.

The present discussion will be presented according to main techniques (>50% contribution to impact) responsible in each project. We start with biological control because this is the one intervention that farmers can control only little. It is therefore considered as the basis for all plant health management. This will be followed by resistant varieties, which was the main contribution of IITA in the first half of this period, then the use of biorational methods and the control by synthetic chemicals, which was the traditional intervention in early IPM, then cultural control, that is good farming practices that are at the root of all other interventions. We shall compare these interventions for different crops and environments, followed by their combination in IPM.

Table 2 Summary of 58 IITA projects

1- Crop etc.	2 - Pest group	3 - Pest	4 - Size of project	5 - Achievements	6 - Percentage contribution						7 - Chapter citation
					Synth. chem.	Biorational	Res. var.	Biocontrol	Cultural	>50%	
Maize	Insect	Fall army worm	5	*publ*	10	30	10	40	10	*mixed*	4
Maize	Fungus	Downy mildew	3	*use**			100			*res*	7
Maize	Insect	Maize stemborers	4	*proof*			15	15	70	*cult*	7
Maize	Insect	Larger grain borer	5	*proof*				20	80	*cult*	7
Maize	Fungus	Mycotoxins	5	*use**		60	20		20	*biorational*	7; 13
Maize	Virus	Maize viruses	5	*use**			80		20	*res*	3; 5
Cassava	Virus	Cassava viruses	5	*use**			80		20	*res*	3; 5
Cassava	Insect	Cassava mealybug	5	*adapt**			5	90	5	*biocon*	6
Cassava	Mite	Cassava greenmite	5	*use**			15	85		*biocon*	6
Cassava	Insect	*Zonocerus*	2	*test*		90			10	*biorational*	6
Cassava	Bacterium	Cassava bacterial blight	3	*proof*			55		45	*res*	6
Cassava	Fungus	Cassava anthracnose	2	*proof*			100			*res*	6
Cassava	Insect	ARTS	2	*proof*					100	*cult*	6
Cassava	Bacterium	Cassava root diseases	1	*publ*				10	90	*cult*	6
Cassava	Plant	Various weeds	2	*unpubl*			10		90	*cult*	14
Yams	Virus	Yam viruses	4	*use*			55		45	*res*	3; 5; 8

Yams	Nematode	Root-knot nematodes	4	*publ*	20	20	20		40	*mixed*	4; 8
Yams	Fungus	Fungal pathogens	4	*publ*		20	10		70	*cult*	8
Cowpea	Virus	Cowpea viruses	1	*publ*			100			*res*	3; 5
Cowpea	Fungus	Anthracnose	1	*proof*	10		80		10	*res*	10
Cowpea	Fungus	Leaf spot	1	*publ*			60		40	*res*	10
Cowpea	Fungus	Charcoal rot	1	*publ*			20	40	40	*mixed*	10
Cowpea	Bacterium	*Xanthomonas*	1	*publ*			60	10	30	*res*	10
Cowpea	Nematode	Root-knot nematodes	1	*publ*			60	20	20	*res*	10
Cowpea	Insect	Cowpea aphids	2	*proof*			40	60		*biocon*	10
Cowpea	Insect	Thrips	3	*proof*	20		40	40		*mixed*	10
Cowpea	Insect	*Maruca* pod borer	4	*use*		20	10	70		*biocon*	10
Cowpea	Insect	*Clavigralla*	2	*proof*	20	10	30	40		*mixed*	10
Soybean	Fungus	Soybean rust	1	*proof*			100			*res*	10
Soybean	Virus	Soybean viruses	1	*publ*			100			*res*	3; 5
Banana	Virus	Banana streak virus	3	*use*			20		80	*cult*	3; 5; 9
Banana	Virus	Banana bunchy top virus	3	*use*			20		80	*cult*	3; 5; 9
Banana	Fungus	*Fusarium* wilt	1	*unpubl*					100	*cult*	9
Banana	Fungus	Black sigatoka	1	*test*	10		20		70	*cult*	9; 14
Banana	Bacterium	*Xanthomonas* wilt	1	*proof*			100			*res*	9

(Continued)

Table 2 *(Continued)*

1- Crop etc.	2 - Pest group	3 - Pest	4 - Size of project	5 - Achievements	6 - Percentage contribution						7 - Chapter citation
					Synth. chem.	Biorational	Res. var.	Biocontrol	Cultural	>50%	
Banana	Nematode	Nematodes	2	*use*					100	*cult*	9
Banana	Insect	Banana weevil	3	*use*	10	20		10	60	*cult*	9
Plantain	Plant	*Chromolaena*	1	*unpubl*	10				90	*cult*	14
Vegetables	Nematode	*Meloidogyne*	2	*use*					100	*cult*	11
Vegetables	Bacteria	*Ralstonia*	2	*proof*			20	20	60	*cult*	11
Vegetables	Insect	Diamond-back moth	2	*use*	10	60		30		*biorational*	11
Vegetables	Insect	Beet web-worm	2	*proof*		100				*biorational*	11
Vegetables	Mite	Broad mite	1	*publ*				100		*biocon*	11
Mango	Insect	Mango mealybug	5	*adapt**				90	10	*biocon*	12
Mango	Insect	*Bactrocera dorsalis*	5	*test*	20			40	40	*mixed*	12
Mango	Insect	Spiralling whitefly	1	*use**				100		*biocon*	12
Mango	Insect	Papaya mealybug	5	*use**				100		*biocon*	12
Cacao	Fungus	*Phytophthora megakarya*	2	*proof*	20		20	20	40	*mixed*	12
Coconut	Mite	Coconut mite	1	*unpubl*				100		*biocon*	12
Cashew	Insect	Cashew wood borer	1	*publ*				10	90	*cult*	12

Sahel	Insect	Locusts	5	*use**		100				*biorational*	13
Savanna	Plant	Speargrass	4	*use**	20			5	75	*cult*	14
Savanna	Plant	*Striga*	5	*use**	5	5	20	10	60	*cult*	14
Savanna/ forest	Plant	*Chromolaena*	1	*test*	5			25	70	*cult*	14
Open water	Plant	Water hyacinth	4	*use**		10		80	10	*biocon*	14
Open water	Plant	Water fern	2	*use**				100		*biocon*	14
Open water	Plant	Water lettuce	3	*use**				100		*biocon*	14
Human health	Insect	Mosquitoes	2	*publ*	20				80	*cult*	16

1 - Crop.
2 - Pest group.
3 - Main target pest(s) in this core activity or project, including follow-up projects with similar goal.
4 - Importance of project: (1) small project with one student, part of supervisor time share, participation of one university, of few years duration, in one African country, supported by one donor; (2) small project with several students, part of supervisor time share, more than one university, of a few years duration, in one to two African countries, often supported by several donors; (3) part of a larger project with a few IITA international staff, several students at various universities, active in a few countries, with support from several donors and, in the past, continuous core funding; (4) large self-standing project with several collaborating supervisors from different CGIAR centres and professors of several universities active in several countries over up to five years, often funded by several donors; (5) large self-standing projects with numerous international staff of different CGIAR centres, other international organizations and universities, with numerous students, active across the continent, funded by an organized donor consortium (eventually planned) over five or more years.
5 - Achievement: *unpubl* - unpublished results concerning implementation; *publ* - scientific results published in peer-reviewed journal; *proof* - proof-of-concept documenting impact under experimental or restricted conditions; *test* - tested under farmers' field conditions; *use* - results ('goodies') and impact are documented and used by governments/NGO/farmers; *adapt* - results from IITA were adapted to new circumstances, extended to other continents or crops; * - with socio-economic analysis; *fail* - activity has later been acknowledged as a failure/failed investment.
6 - Contributing factors to success in % (very rough estimates) after the project has been implemented: % control by synthetic chemicals, % biorational control (including botanicals, Bt, fungi, viruses etc.), % biological control with insects, mites (introducing agents or favouring existing agents) including competitive exclusion, % resistant varieties, % cultural practices, including phytosanitation and use of virus-free planting material. Contribution >50%, if all <50% = mixed.
7 - Citation: Chapter number in this volume.

3.1 The impact of IITA projects: biological control

3.1.1 Comparing results

Biological control is mentioned in 30 projects, and in 12 of them it was the most important (>50%), in six even the only component. Averaging the confounded criterion for importance and size of the project with values from column 4 (Table 2), over all 12 projects dominated by biological control interventions, yielded a score of 3.2. All these projects collaborated with other institutions exchanging material, relying on an international network and fraternity of biological control scientists. Nine projects (30%) remained academic studies, nine (30%) reached proof-of-concept stage or were already tested in the field and 12 were in use by farmers (40%). Among the 12 projects with predominantly biological control input, six had size 4 or 5 and reached the stage of *use* or even *adaptation*. In two of these cases, IITA provided material to other continents (Wyckhuys et al., 2018a), repeating the impact of biological control often without additional financial support. Three projects with size 1 or 2 did not go beyond *proof* of concept, indicating that bigger projects generally brought higher rewards. Yet, three projects had high impact (*use* or *adapt*) with minimal input (1 or 2). Those were mostly projects without proper funding, which we could execute thanks to personal relations ('old-boys' network') by receiving already tested agents for free. Most of our biological control successes concerned using specific hymenopterous parasitoids against Hemiptera, slightly polyphagous phytoseiid mites against other mites, or specific curculionid beetles against plant pests, thereby confirming rather old international statistics (https://www.cabi.org/isc).

Interestingly, classical measures of efficiency of natural enemies (the intrinsic rate of natural increase r_m for instance) did not well predict the actual impact of some natural enemies in the field (Chapter 6). *Anagyrus lopezi*, the parasitoid that brought cassava mealybug under control, had a low r_m, but achieved its success thanks to its exceptional host-finding and strong dispersal capacities. Similarly, the most promising phytoseiid mite predator of cassava green mite, *Typhlodromalus aripo,* had a low reproductive capacity, but excelled because of its habitat choice, which corresponded to the one of its prey, and its capability to remain on the host plant throughout the year thanks to its utilization of alternative food sources. While assessing the reproductive capacity under laboratory conditions gives useful data for population modelling, the above cases highlight that these studies should be followed up by ecological and behavioural studies in order to understand and better exploit natural enemies.

In most projects, taxonomic problems were encountered (Chapter 4), be it at the level of the host plant (e.g. *Chromolaena,* Chapter 14), the pest (e.g. *Maruca,* Chapter 10; *Aspergillus*, Chapter 8) or its natural enemies

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(*Anagyrus, Neoseiulus,* Chapter 6; *Phanerotoma,* Chapter 10). This underlines the importance of having a taxonomic capacity as realized in the staff of the biodiversity collection at IITA-Benin. In close collaboration with this biodiversity centre, most biocontrol projects invested in studies of food webs, indicating which hosts were attacked by which natural enemies. Importantly, none of the often-criticized non-target effects (Lynch and Thomas, 2000; Roy et al., 2016) were reported. These studies were, however, hampered by the often still weak taxonomic knowledge about indigenous insects in tropical Africa.

A high degree of biological control has been achieved and documented mainly for exotic pests: cassava mealybug, cassava green mite (Chapter 6), mango and papaya mealybugs, spiralling whitefly (Chapter 12) and floating water weeds (Chapter 14). On mandated crops, these biological control projects always revealed that some existing varieties were less susceptible to the invader than others and were worthy to be recommended, thereby demonstrating that biological control interventions were generally fully compatible with existing resistant varieties (Thomas and Waage, 1996). A better consideration of the effect of the host plant on natural enemies, as for instance selecting for 'domatia' - shelters for *T. aripo* on cassava (Chapter 6) - or hairiness of leaves on the performance of small parasitoids, could open up new prospects for IPM (Wang et al., 2009; Pickett et al., 2014; Stenberg et al., 2015).

In addition, several studies revealed incipient successes by providing 'proof of concept' for the effect of natural enemies against several exotic pest species. Four projects demonstrated unexploited potential for biological control based on improved taxonomic studies.

In the case of *Maruca* pod borer (Chapter 10), which was generally assumed to be of African origin, taxonomic studies indicated an Asian origin (with new complications mentioned in Chapter 4), thereby opening up the possibility for classical biological control, which is starting to show an incipient success.

Similarly, better control of larger grain borer might still be achieved across Africa by exploiting different sources of predators (Chapter 7). The same is true for the control of different biotypes of *Chromolaena* of different origins (Chapter 14). Finally, inner-African differences among stem borers and their parasitoids were exploited for classical biological control, as shown in first feasibility studies (Chapter 7).

In the case of the new fruit fly attacking mangoes and citrus, later identified as *Bactrocera orientalis,* a parasitoid has now been established and is slowly spreading (Chapter 12). Though biological control of fruit flies has famous precedents (van den Bosch et al., 1951), it has in recent cases proven to be difficult and requiring an IPM approach including augmentative releases of parasitoids and sterile male techniques (Rousse and Quilici, 2009).

In all these cases, further studies that go well beyond the funding periods of the corresponding projects are necessary to measure and perhaps explain the slowness of impact of released natural enemies – or arrive at the conclusion that the equilibrium levels achieved by the released and established agents are unacceptably high.

Despite some abuse of pesticides, often in confined conditions as in vegetables (Chapter 11), but also in cowpea (Chapter 10), cocoa (Chapter 12) and other cash crops, African small-scale agriculture is still relatively free of pesticides and could be called 'organic'. Considering the huge numbers of insect species present in these tropical environments, indigenous pest species are indeed astonishingly few (Prinsloo and Uys, 2015). Natural biological control, though mostly undocumented, evidently plays an important role. It is often only recognized when indigenous natural enemies are being killed by insecticide treatments that make pests out of many spider mites, leaf-mining flies and others. This control is often achieved through non-specific natural enemies (Chapter 11). Similarly, abusive insecticide applications against fruit flies endangered the well-established biological control on mango mealybug, requiring now the development of a holistic IPM approach encompassing all pests on mango (Chapter 12).

Yet, difficult-to-tackle problems with indigenous pest species remain. Most stem borers on maize, sorghum and sugar cane (Chapter 7), cowpea thrips (Chapter 10), witch weeds on maize and legumes (Chapter 14), and all indigenous field and submersed weeds (Chapter 14) remain problematic. Classical biological control against them is no option, but inundative releases of natural enemies can be envisaged. Because of the problematic logistics of large-scale insect rearing this approach has been difficult in tropical Africa, but favouring parasitoids through changes in the environment like shelters or alternative host plants has given good results (Chapter 10; Guerci et al., 2018). Generally, control against indigenous pest species requires an array of IPM interventions and, in the case of parasitic weeds like *Striga* (Chapter 14), will concern mainly the management of soil fertility.

Increasingly, IITA's R4D is influenced and guided by international treaties. Since its first biological control projects, IITA was involved in the development of guidelines for the import and release of natural enemies (FAO, 1996) and has since meticulously followed the FAO recommendations. More recently, the Intergovernmental Panel on Climate Change (IPCC, 2014) gives directions to reduce CO_2 emissions, to prepare breeding programmes for higher temperatures and lower rainfall, and to study the influence of a changed climate on food webs, particularly the relationship between natural enemies, their phytophagous hosts and their host plants. The corresponding and much younger Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services with its focus on the epic disappearance of plant and animal

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populations still struggles to include players also in developing countries and foster economic and sociological analyses to reach the same acceptance as the IPCC (Masood, 2018).

The best estimates about the health of the biosphere come from studies of birds, a particularly well-known and popular taxon. These studies show that among the 1469 globally threatened species, 74% are disappearing because of agriculture, a far higher number than the one attributed to any other activity like logging or hunting (Birdlife, 2018). IITA with its goal to further agricultural production for people therefore rightly focusses on the sustainability of its technologies. Thus, ecosystem services are discussed in many projects and IITA participated in worldwide projects on classical biological control for the protection of natural ecosystems (van Driesche et al., 2010; Chapter 14). Nature's contribution to people is increasingly taken into account in research and led to fruitful collaboration with non-academic activists for nature protection (Chapter 4) as suggested by McNeely and Scherr (2001) and recently stated more generally by Kremen and Merenlender (2018).

3.1.2 Challenges

Alien exotic species continue to reach Africa and force us to find long-lasting solutions. In eastern Africa, five major invasive alien species threaten smallholder mixed maize farming in Ethiopia, Kenya, Malawi, Rwanda, Tanzania and Uganda (Pratt et al., 2017). Thus, spotted stem borer (*Chilo partellus*), maize lethal necrosis disease, the weed *Parthenium hysterophorus*, the *Liriomyza* leaf-miner complex and the South American tomato leaf-miner *Tuta absoluta* caused annual losses of US$0.9–1.1 billion on mixed maize smallholders in these six countries alone. Losses are likely to increase as the weed and pests continue to spread.

Another example concerns the environmental and economic costs of invasive alien plants in South Africa (van Wilgen and De Lange, 2011). Costs for lost water, diminished grazing and negative impacts on biodiversity are estimated at US$450 million p.a., and could rise to >5% of GDP if invasive plants are allowed to reach their full potential.

Finally, the estimated losses caused by the recent invasion of fall army worm (FAW) correspond to 21–53% of the annual maize production in Africa, or between US$2.5 and US$6.2 billion annually. Other food crops are also likely to suffer losses from FAW (Prasanna et al., 2018).

Biological control against such invasive exotic pests is the method of choice and in the past yielded benefits that equalled whole breeding programmes (Neuenschwander, 2004). Yet, classical biological control programmes face opposition (starting with Howarth, 1991), because of the widespread abhorrence of anything exotic fuelled by scientists in North America and Europe

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and transferred to Africa by some NGOs. Fortunately, viewing the spread of organisms as inherently natural - in opposition to the dogmatic view of anything exotic as being 'unnatural' that is needing extirpation - is gaining importance (Guiaşu, 2016). IITA's practical view is to interfere only on request by clients and only under severe damage. We respond to cries of alarm. Therefore, not every new insect or pathogen becomes a target. Ideally, projects are coupled with a cost:benefit analysis before launching a classical biological control programme. Such programmes generally are an initially expensive, government-controlled action that does not need much involvement by farmers because introduced agents spread on their own.

Under these premises, one recurrent practical problem concerns the timing of the intervention. Cassava mealybug, for instance, was allowed to spread and do damage for years before the logistics of foreign exploration, external quarantine and natural enemy rearing could be tackled satisfactorily (Chapter 6). When, after many years, an efficient parasitoid had been found and reared and all import permits and so on were ready, damage was huge and subsequent control spectacular. In the case of papaya mealybug (Chapter 12), educated personnel, facilities and knowledge at the level of quarantine authorities were ready, control was equally spectacular, even faster than against cassava mealybug, but publicity and corresponding recognition were much lower, if not absent. Consequently, project funding was limited and did not allow as much basic research, which advances the science of biological control, as in the case of cassava mealybug. For the control of spiralling whitefly (Chapter 12), procedures for importing the proven parasitoids were well advanced when these turned up serendipitously.

With some pest groups, as for instance leaf-miner flies, whose parasitoids do not attack the larvae directly but lay their eggs into the mine, whereupon the parasitoid larva searches its prey by itself, indigenous parasitoids have been shown to control these exotic invaders (Neuenschwander et al., 1987). Such control of exotic invaders by indigenous natural enemies very much depends on the systems involved and remains controversial (Levine et al., 2004). While already present natural enemies might eventually adapt through evolution to control all invaders, this is not a practical approach against threatening pests in Africa. Since adaptation has already occurred in the homelands of such invaders we can profit from natural enemies found during foreign exploration. Unfortunately, permits for such search and the necessary exportation have become increasingly difficult to obtain from countries like Brazil, India and others (Chapters 8 and 10).

Many new pests are difficult to identify, sometimes still unknown; the same applies for their parasitoids and predators (Chapter 4). Tests for accepting potential biological control agents for introduction generally ask about specificity and potential non-target insects, which in the African environment are often not yet known. Such studies demand a permanent in-house taxonomic capacity and worldwide links with other taxonomic institutions, which in a strictly project-based institute remains a problem. A parallel support and recognition of the Biodiversity Center in IITA-Cotonou for non-plant genetic resources as for the Genetic Resources Unit at IITA-Ibadan for plant resources is therefore the ultimate aim. Ideally, such institutions should also be created on other continents, and work together with CAB International, which has the greatest capacity in foreign exploration worldwide.

The initial impact of an invading exotic pest is often forgotten when, following the establishment of exotic natural enemies, population densities are kept below economic thresholds (mostly undefined) for years. Subsequent upsurges are therefore often dramatized, even if they are within the normal fluctuations. Or sometimes they are the consequence of insecticide abuse on other pests, which calls for integration in IPM programme. Sometimes, the new introduction concerns unrecognized sibling (of not yet described) species requiring further taxonomic studies (Chapter 4). Resurgences or incomplete successes can also be due to missing or neglected ecological links, for example missing alternative host plants during off-season on cowpea pests (Chapter 10). Which of these scenarios applies is often difficult to assess. Generally, larger resurgences, which are not attributable to insecticide misuse, should always be subjected to DNA-based identifications. Moreover, food web and competitive displacement studies as applied in many projects instead of linear predator-prey studies can give the necessary answers to stabilize the system.

None of the listed projects was reported as an absolute failure. As is usual in classical biological control though, many introduced parasitoids, coccinellid predators and phytoseiid predators could not establish. Detailed studies about these natural enemies sometimes revealed the reasons for their non-establishment or inefficiency, thereby contributing to the general science of biological control (Chapters 6, 7, 10 and 12). It must be stressed, however, that such non-established and in quarantine tested organisms do not cause ecological harm. Across all projects worldwide only about one in six organisms can be established as a natural enemy (Bellows, 2001). Such failures are part of biological control endeavours (much as crop varieties that are not accepted by farmers, or chemical compounds that eventually do not result in marketable pesticides). In each project, releasing several natural enemy species at the same time, though not in the same locations, is therefore an accepted practice and does not hinder establishment of the fittest, though this procedure is still discussed controversially (Osborne and Cuda, 2003).

Unfortunately, most classical and other biological control interventions have a relatively slow impact. An example is the desired transition from a pesticide to a biological control-dominated schedule, for instance when FAW is first subjected to chemical control before classical biological control options will be ripe for implementation (Prasanna et al., 2018; Chapters 4 and 7). Impact assessments of classical biological control introductions sometimes take years – too long for short project funding. A series of potential biological control successes mentioned above could therefore not be correctly evaluated as the problem seemingly faded from the scene and further demand by African clients was lacking. While donors will fund implementation and maybe economic impact assessment, they certainly do not give additional funds to carry out a final ecological assessment that might provide knowledge about reasons for success or failure: larger grain borer, water hyacinth, cowpea thrips and *Chromolaena* fall into this category. Unfortunately, these projects also do not provide good researchable (for PhD) topics because of the needed vast coverages and long durations.

3.1.3 The way ahead

Generally, judiciously implemented biological control can deliver ample 'hidden' environmental and human health benefits that are not captured by the prices of globally traded commodities (Wyckhuys et al., 2018b). Yet, full-scale quantitative studies considering socio-economic parameters are uncommon (about biological control successes see Neuenschwander, 2004; about pathogens Savary et al., 2012). To improve the effectiveness of research prioritization and impact assessment, the biophysical spatial framework as well as appropriate socio-economic attributes (Edreira et al., 2018) should be included in each project document, with final surveys to be executed several years after the completion of the project.

Despite improved quarantine measures, introductions of potential pests into Africa and across the globe continue and are likely to increase in the future (Seebens et al., 2018). Experience with cassava mealybug and other Hemiptera shows that, where new introductions lead to widespread serious damage, all financial support should go into biological control projects first. Since many pests for instance from South America (Bellotti et al., 2012; Bellotti, 2017) have not yet been accidentally introduced into Africa, an effective horizon scanning and early warning system for anticipated introductions is required together with improved quarantine services.

Judging when to attack invasive insects remains, however, tricky: on the one hand, it will be cheaper to fund proactive initiatives, even extermination of small foci, rather than use the firefighter approach as for FAW; on the other hand, some invasive species are later followed by their also exotic effective parasitoids, like spiralling whitefly, while others are controlled by indigenous parasitoids and predators, like leaf-mining flies as discussed above. Generally, a more efficient uptake of biological control practices is needed (Barratt et al., 2017).

3.2 The impact of IITA projects: resistant varieties

3.2.1 Comparing results

Resistant varieties are mentioned in 33 projects, and in 14 of them this was the most important (>50%), in six even the only, component. The mean importance and size of these 12 projects yielded a score of 2.2. Ten projects (31.3%) remained academic studies, 12 (37.5%) reached proof-of-concept stage or were already tested in the field and 10 (31.3%) were in use by farmers. Among the 14 projects with predominantly resistant variety input, three had size 4 or 5, that is reached the stage of *use*. Ten projects with size 1 to 3 did not go beyond *proof* of concept, again indicating that bigger projects generally brought higher rewards.

As a follow-up of the Green Revolution and the establishment of the CGIAR, the development of resistant varieties became the mainstay of plant protection for the first half of the indicated period (Chapter 2; review in Eriksson et al. 2018). Today, the use of host plant resistance is guided by the nature of crop-pest interactions, pest ecology and pathogen epidemiology, and the availability of novel resistant genes discovered with modern genomic tools. Generally, main successes in host plant resistance were achieved against bacterial, fungal and viral diseases. Against nematodes, impact was smaller because of the diversity of species involved. Resistance breeding against arthropod pests of IITA-mandated crops has proven more difficult and has only resulted, so far, in a number of resistant genotypes mostly tested under screen-house conditions (Chapters 7, 10 and 11). In addition, resistant varieties have been relevant in the broad context of IPM in combination with other compatible management options, but not as stand-alone interventions.

One of the first major breakthroughs in developing resistant varieties at IITA was achieved way back in 1972, when the cassava mosaic disease (CMD)-resistant genotype TMS 30572 was first cloned and later widely disseminated in Africa. Today, it remains one of the most popular cassava varieties still retaining the original level of resistance to CMD (Chapter 5). Other cassava pathogens such as cassava anthracnose disease can also be effectively managed by resistance breeding (Chapter 6).

Another breakthrough was achieved in the control of a downy mildew strain affecting maize, which appeared in the 1990s as an emerging disease in Nigeria. The successful approach included the development of a new screening methodology. The quantity of seeds of resistant varieties necessary to contain the epidemic could only be overcome by a concerted donor support for large-scale seed distribution schemes. As a result, the downy mildew epidemic was stopped in 2000, and the disease has not been reported anymore from Nigeria until today (Chapter 7). A similar success was achieved in controlling maize streak virus, which culminated in the 1990s with the release and farmer adoption of resistant varieties, often produced by national partners using sources of resistance discovered by IITA. However, these successes have recently been threatened by emerging epidemics caused by maize lethal necrosis. Efforts are currently underway to combine resistance genes against both viruses.

Other efforts to develop and deploy host plant resistance have not yet yielded the same scalable successes. Most of the available resistance is currently at the proof-of-concept level. Good examples for promising interventions are the development of aphid- and thrips-resistant cowpea varieties using modern and efficient phenotyping protocols, whereby hundreds of accessions from the IITA mini-core collection can be evaluated in a short time (Chapter 10). Coupled with new breeding approaches such as marker-assisted recurrent selection, there is hope for faster and more targeted progress to find durable resistance sources against these two pests.

Another interesting example is given by the lessons learned during the quest for resistance sources against the Asian soybean rust (ASR) which started to cause widespread epidemics in Africa in the mid-1990s. All varieties produced at that time in Africa were highly susceptible to the disease. Subsequently, some varieties with good levels of resistance were found, which are still being used today. However, ASR is capable of recombining into more virulent pathotypes, which needs monitoring using modern surveillance tools. At the same time, ASR-resistant genes are to be stacked for developing varieties with more durable resistance (Chapter 10).

Because of their intractable nature with conventional resistance breeding, banana *Xanthomonas* wilt (Chapter 9) and legume pod borer (Chapter 10) have been the object of intensified efforts to develop transgenic products. While IITA geneticists and breeders were the initiators of the transformation of bananas with two genes obtained from bell pepper, they were only marginally involved in the initiative to transform cowpea with the Cry1Ab gene construct to confer resistance against the legume pod borer. Both GM banana and cowpea varieties are currently tested under confined field trials in view of obtaining a deregulation under the prevailing national biosecurity laws.

3.2.2 Challenges

Perhaps the most disrupting challenge in host plant resistance breeding is the break down of good resistance levels already after a few years following their introduction due to mutations in the target pest organisms (Thrall et al., 2011). One of the classic examples was the loss of resistance in cowpea against the aphid *Aphis craccivora*, which had been mediated by a single dominant gene. Soon after the release of the resistant variety, new biotypes of the pest appeared, which were able to circumvent the resistant mechanism (Chapter 10). Other problematic organisms with high pathovar mutations are rust pathogens, as seen above for ASR.

Another technical obstacle in resistance breeding is the presence of co-infections with different types of plant pathogenic viruses. While improved screening methodologies yielded a number of cowpea lines highly resistant to potyviruses, this progress was halted by the presence of other viruses (cucumber mosaic virus, which belongs to the Bromoviridae) in the same plant tissue, which caused synergistic interactions. This problem has now been overcome by modifying the screening protocols for including co-infections in the selection process (Chapter 10).

One more recurring issue is the question of how to maintain high yields in existing varieties, while attempting to introgress resistant traits. Such resistance genes might have existed in the wild ancestors of the crop, but were inadvertently removed during the process of domestication and subsequent efforts to breed for high yields, as for example was the case during the Green Revolution. So the dilemma here is about the possible trade-offs between yield and resistance. As mentioned in the last section, there are some biotechnological approaches to this, but their application, so far, remains at the proof-of-concept level (Douglas, 2018).

As usual in plant breeding, only a small fraction of the genotypes with promising attributes is eventually developed into varieties that are given for free to national research programmes, for them to be named and/or adapted to their local conditions. During this process, the IITA origin is often lost, which in itself is what the CGIAR welcomes as part of the creation of international public goods. This approach can, however, pose problems of attribution when IITA's impact is being evaluated, for example by donor agencies funding that particular research.

With the advent of modern biotechnological tools leading to widespread deployment of transgenic crops, most conventional resistance breeding approaches have been abandoned in the developed world (Douglas, 2018). Also in African national programmes as well as at IITA, the modernization of breeding programmes has led to increased use of marker-assisted selection and other novel techniques. As mentioned above, two GMOs, transgenic bananas and cowpea, are now close to commercialization. However, they might face challenges in their implementation in most African countries, where the corresponding legal framework is still not ready. Compounding this problem is the weak seed (and tissue culture) production and distribution system, with low investments by national governments, and only marginal interest by the multinational private seed producing companies which prefer to invest in mainstream crops such as maize. However, with the further introduction of newer techniques such as CRISPR genome editing (Georges and Ray, 2017; Ryffel, 2017), which are posited to be more environmentally friendly and less controversial than, for example *Bt*-transformed crops, there might be new avenues for a true integration of GMOs into sustainably managed agro-ecosystems close to organic agriculture under a resistance management plan that would be easily implementable by low-literacy farmers (Ammann, 2007).

As already mentioned for biological control interventions, taxonomic problems - mostly misidentification of noxious organisms - can also hamper progress in host plant resistance (Chapter 4). Moreover, resistant traits are often species- and even strain-specific, so this needs to be taken into consideration when screening for resistant genotypes. To maintain this pool for the future development of new varieties, it is essential to maintain the genetic diversity of crop plants (Louwaars, 2018).

3.2.3 The way ahead

The CGIAR system is currently undergoing profound changes in its approach to breeding, particularly through its Excellence in Breeding Platform (http://excellenceinbreeding.org). It aims at more clearly defining breeding priorities by fixing client-oriented product profiles, an approach borrowed from the private sector. This new paradigm will also have implications for resistance breeding, whereby modern genotyping, phenotyping and bioinformatics tools will be applied throughout the product development pipeline.

The question remains whether these novel approaches will allow for the development of new varieties which can deliver metabolites and semiochemicals, for example those attracting biological control agents, or repelling herbivores (Wang et al., 2009; Pickett et al., 2014; Stenberg et al., 2015). In the past, breeders have been steadily responding to research managers, donors and possibly farmers by focussing mainly on 'genetic gains'. Today, there exist opportunities for re-visiting the way varieties should interact with their environment, including traits that can actively mediate plant-pest-natural enemies interactions. An even more unconventional approach concerns the modification of plants to deliver anti-microbial substances capable of suppressing endosymbionts in insects such as aphids, or to use microbial endosymbionts to deliver RNAi techniques; however, both approaches are still confined to the lab, with foreseeable challenges facing the fate of genetically modified microorganisms in the environment (Douglas, 2018).

Particularly since the wake-up call from the catastrophic invasion of FAW, IITA should be on the alert for new, potentially destructive invasive alien species. In fact, most staple crops in Africa are of exotic origin, and there are still a number of pests and diseases occurring in their respective area of origin, which are fortunately not present on our continent. These include, for example frog skin disease, superelongation disease and the witches' broom disease of cassava (Chapter 7). Being informed of such diseases and their causal agents, mode of spread as well as their impact is important in order to activate existing tools, for example sensitization, phytosanitary measures, efficient diagnosis and surveillance if an accidental introduction occurs. Perhaps more importantly, pathologists and breeders should be proactive in planning for a rapid response, which will mainly rely on resistance breeding in case of plant pathogens.

3.3 The impact of IITA projects: cultural and environmental control

3.3.1 Comparing results

Among most cultural practices developed at IITA in collaboration with extension services and farmers, relatively few address plant health protection or improvement directly. Cultural practices concerning phytosanitation and the use of virus-free planting material are mentioned in 38 projects, and in 20 of them it was the most important (>50%), in four even the only component. The mean importance and size of the 20 projects yielded a score of 2.4. Seven projects (35%) remained academic studies, six (30%) reached proof-of-concept stage or were already tested in the field and seven (35%) are in use by farmers. Among the 20 projects with predominantly cultural practices input, five had size 4 or 5, but only two of them reached the stage of *use*. The other five with *use* had only size 2 or 3. In other words, there was no relation between input as indicated by size of the project and its achievement.

Much of this type of control falls under the designation of 'good agricultural practices' and its success and adoption rate often depends on the local environment and is hence difficult to scale out without modifications. Moreover, all techniques require the active involvement of the farmers, their households and sometimes even entire villages, in order to assure impact. Farmers' education and gender-sensitive approaches are therefore at the heart of implementing these techniques.

One rather unconventional cultural control approach to clean plantain suckers of nematodes and weevils was developed for smallholder farmers in Central Africa (Chapter 9). A first version of this approach was contemplating the use of a high-volume tank of water, which was gradually heated to a constant temperature of 52°C. Suckers were submerged in the hot water for about 20 min, which would clean them of nematodes and weevils. However, this system was rather difficult to transport and assemble, required a substantial initial investment and proved difficult to operate by unskilled farmers. Hence, it was simplified by using locally available implements such as large cooking pans. Water would be boiling in these pans, and the suckers dipped in the boiling water for some 30 s. This approach delivered the same pest-free quality suckers as the first method, but with significantly less investment and labour.

Attempts at using cultural control to manage problem weeds showed good levels of technical performance, but remained largely non-adopted (Chapter 14). The introduction of cover or alley crops to control speargrass is such an example. In fact, planted fallows with *Mucuna* spp. and *Gliricidia* trees arranged as alleys were able to suppress *Imperata* over several years, but farmers did not find enough incentives to be able to perceive these technologies as profitable. Similarly, *Striga* management offered many promising technical approaches, but implementation was sporadic (Chapter 14).

3.3.2 Challenges

The main problem with cultural control can be described in simple terms as the lack of immediate, visible and direct benefit to the farmer. The most striking example is the non-adoption of the cover crop *Mucuna* for speargrass control in West Africa, which was related to negative attributes of its seeds (neither commercial nor nutritional value, lack of availability) on the one side, and perceived negative impacts on cropping systems (reduction of available cropping surface, competition with short duration crops and prone to dry season fires), on the other hand. The same fate occurred to alley cropping, where additional labour, water and nutrient competition, and interference with established cropping practices were perceived as key determinants for poor or non-adoption of the technique (Mutsaers et al., 2017).

This is not astonishing since traditional coping strategies by farmers mostly consider yield increases in the short term, often within a single cropping season. Long-term strategies and related investments are considered too risky in prevalently rain-fed African agriculture. This is also the case for approaches for managing the parasitic weed *Striga*, where several options were developed, but the adoption rate remained stagnant because of this lack of long-term perspective and difficulty of explaining in order to obtain commitment by low-literacy farmers.

It also needs to be emphasized that cultural control recommendations often are highly location-specific and sometimes difficult to transfer to other agro-ecological conditions. Stronger partnership with national programmes is particularly important here, because grass-roots staff in extension services, development projects and NGOs is best placed to implement and adapt such results.

3.3.3 The way ahead

As we have seen for the sucker-boiling technique, often simple but efficient methodologies can prevent losses. However, because of the lack of scaling pathways, mainly due to the inability to attract corresponding funding for such approaches, which are not as 'flashy' as breakthroughs in genetic gains, these efforts remain largely at local levels, often not well documented and even less widely appreciated. Yet, without good soil and weed management, the best improved varieties will not be able to express their full yield potential, and even biological control agents will perform poorly under such conditions. Similarly, a more sustainable and robust *Striga* reduction strategy should promote scientifically proven technologies co-developed with farming communities and provide tangible impacts on improving soil fertility, stopping *Striga* emergence, reducing the *Striga* seed bank and improving crop yields. Most soil-related biotic stresses such as *Striga* and nematodes can be considered symptoms of bad soil management requiring a holistic soil health management, that is 'improved' cultural practices. This implies that research results, which yield successes at the local level, are to be communicated and scaled out for wider adoption and impact. The generation and transfer of appropriate and gender-sensitive knowledge capable of transforming the way low-literacy farmers perceive agriculture is therefore critical.

Cultural practices were, however, not always tested in environments where they were most needed, that is where the farmers were with 'their backs to the wall' and had no other options anymore, as detailed in the appropriate GIS-based maps. Both mentioned practices fared better when introduced for instance in an area of low-fertility in the Mono Province of Benin: alley-cropping trees for farmers who owned their land and *Mucuna* for those who only rented it. Moreover, most tree species introduced in alley-cropping trials have now found their application as solid wood lots (Douthwaite et al., 2002; Carsky et al., 2002). It is concluded that considering cultural practices not as silver bullets, but as highly targeted options for adaptation by farmers will improve their success rate.

3.4 The impact of IITA projects: biorational control including use of botanicals and entomopathogens

3.4.1 Comparing results

Biorational control is mentioned in 14 projects; in five of them it was the most important (>50%) and in two even the only component. The mean importance and size of the five projects yielded a score of 3.2. Two projects (40%) reached only proof-of-concept stage and three (60%) are now in use by farmers. Among the five projects employing predominantly biorational methods, two had size

5, both reaching the stage of *use*. The other three had only size 2, but one of them still reached *use*.

The outstanding successes of two key products from the IITA 'kitchen', Green Muscle® and Aflasafe®, were only possible thanks to major investments by the donor community (Chapters 7 and 13). Private manufacturers were supposed to take up the relay in large-scale production and commercialization, but both approaches have still not reached cruising speed. Other biorational products of perhaps equal potential for impact have remained at the proof-of-concept level and continue to rely on the IITA-Benin pilot production unit for farmer demonstration trials. One of them is a diamond-back moth – active strain of the entomopathogenic fungus *Beauveria bassiana*, which has demonstrated excellent performance against this key pest of cabbage (Chapter 12), but has remained on the starting blocks owing to the lack of large-scale production.

3.4.2 Challenges

As opposed to East Africa, where export commodities such as cut flowers and green beans have driven the development of a competitive bio-pesticide industry to overcome excessive pesticide residue levels, there have been no similar developments in West Africa. Due to the lack of alternatives, horticultural farmers in particular are still using hazardous chemical pesticides, often of doubtful quality, in an attempt to save their yields. An exception to this scenario is currently happening in Benin, where at local levels, there has been a substantial increase in the production and supply of neem oil and derived products, with increasing demand also from neighbouring countries. Four key drivers are responsible for this recent development: (1) the efficacy of neem-derived biorationals against a range of pests in various cropping systems; (2) the competitive price as compared to chemical pesticides; (3) the growing perception of the health and environmental hazards posed by the indiscriminate use of pesticides; and (4) the development of a value chain around neem by-products, including oil cake, which is a good source of organic fertilizer with concurrent nematicidal properties (Chapters 10 and 11).

3.4.3 The way ahead

While IITA has been prominent in developing biorationals, we do not have a clear comparative advantage in their production and commercialization. This should be the prerogative of the private sector. Also, venturing into commercial production and the ensuing need for covering it with patenting rights might conflict with the CGIAR open access policy. All this calls for strengthening our collaboration with the private bio-pesticide industry, possibly through some innovative forms of partnership and financial co-investments.

3.5 The impact of IITA projects: chemical control

3.5.1 Comparing results

The use of synthetic chemicals is mentioned in 15 out of the 58 projects (25.9%) only, mostly as a small component of up to 20%. Evidently, IITA's research develops environmentally friendly technologies in line with the IITA Refreshed Strategy 2012–20 (see below). As further developed in the next section about IPM, chemical control should be used as the last resort to rescue a crop from total failure, before other more sustainable control options are developed and implemented. This is best illustrated for the case of FAW.

In some projects, pesticides are used as seed coating (Chapter 14) or in bait sprays (Chapter 12), methods that do not much pollute the environment. Others are sprayed openly, among them many herbicides that in the past were considered harmless.

3.5.2 Challenges

IITA does not actively conduct research in developing or testing chemical pesticides; this is the mainstay of industry. However, IITA scientists, particularly in the early days of the cowpea programme, have been screening insecticides, mainly with the purpose of using the most efficient ones to protect their breeding plots. Moreover, recommendations for the use of pesticides usually come from national regulatory services and authorities, which in most cases adhere to standard rules such as the ones published by WHO (2009).

So, what are the main challenges for applying pesticides at the farm level? As noted in Chapters 10, 12 and 15, farmers are not always aware of the degree of danger they expose themselves to by applying chemical pesticides without any protecting equipment. This insufficient knowledge is compounded by the high costs related to the purchase of such implements, together with the discomfort of wearing them under a hot and humid tropical climate. The nature and quality of the pesticides themselves can have serious implications for human and environmental health. While there exist lists of recommended pesticides for different cropping systems, pesticide resellers – often untrained – offer to the farming community what sells 'well', that is pesticides that are cheaper than the recommended ones, mostly re-packaged imports from Asia and of doubtful quality. Often insecticides for example against cotton pests are deviated and used on cowpea, against store product pest and so on. Insecticides against agricultural pests, which are seeping into rivers and groundwater, also affect mosquitoes and lead to resistance against malaria (Yadouleton et al., 2011; Djouaka et al., 2016).

But why are the recommended pesticides more expensive? Only the tiniest fraction of synthetic chemical compounds eventually makes it to commercialization as a pesticide. The risks and costs are entirely carried by the chemical industry, which needs to recoup its expenses. Specificity is more and more required and also possible, but reduces the market and increases prices.

3.5.3 The way ahead

As highlighted in Chapter 15, there is still scope for integrating chemical pesticides into IPM schemes, particularly low-toxicity and specific ones, such as those used for seed coating against *Striga*, which certainly offer an environmentally friendly solution. However, the price of those products is most often beyond the means of subsistence farmers, or they are simply not available because of marginal interest for pesticide distributors and resellers.

Recently, special concerns were voiced regarding neonicotinoids and their effects, for instance, on bees (Godfray et al., 2014). Though these are insecticides that are mostly too expensive for our farmers, these warnings should be heeded in order not to repeat mistakes made elsewhere. Similarly, the herbicide glyphosate, which is effective against problematic weeds such as speargrass, will probably be phased out in Europe by 2020 because of its alleged potential for promoting cancer (IARC, 2017). It should therefore also be considered dangerous for Africans, and illiteracy and poverty not accepted as excuses for its indiscriminate use in Africa. Instead, other IPM interventions and products should be promoted.

The practical approach of our IITA plant health team is to try, wherever possible, to enforce the notion of not using pesticides unless there is an emergency situation, and surely not as the first and sole option. At the same time, we should continue the discourse with the industry, to make it aware that biorationals can be as efficient as chemical pesticides, and very often cheaper in production, while keeping in line with the need to make a profit.

3.6 The impact of IITA projects: combining techniques in IPM

3.6.1 Comparing results

In 7 out of 58 projects, no single technology predominated, that is, contributed over 50%. Three of them (42.9%) remained academic studies, four (57.1%) reached proof-of-concept stage or were tested, but none was employed. Among all 58 projects, 18 employed only one technology while 40 (69.0%) employed several techniques, thereby fulfilling the criteria for IPM. However, it needs to be emphasized that by implementing several options simultaneously without a proper concerted effort does not necessarily qualify as IPM. Currently, best examples of IPM implementation are given for cowpea and horticultural crops. In the past, these two systems have accounted for the highest occurrence of indiscriminate use of pesticides, but gradually they are on the path to applying novel approaches in IPM. For cowpea in particular, there exists a number of compatible insect management options ranging from biological control agents (against aphids, thrips and pod borers), resistant/tolerant varieties (mainly aphids and thrips), specific (e.g. baculoviruses) and broad-spectrum biopesticides (neem products), which can all be combined to obtain a synergistic effect in the field (Agunbiade et al., 2014; Chapter 10).

3.6.2 Challenges

To be functional, IPM needs to be understood, accepted and properly practised by farmers beyond the lifespan of yet another donor-funded IPM project. This is possibly the most critical aspect of IPM, which per se is a knowledge-intensive approach. IPM was 'invented' mainly to reduce inappropriate pesticide applications, but was often used as a legitimacy exercise to spray them in good conscience (Chapters 2 and 15). The old IPM paradigm was focussing on the notion of operational thresholds for applying pesticides - economic, intervention and damage thresholds - all without incorporating health and environmental considerations. This concept was difficult to understand by low-literacy farmers, even when inculcated through participatory approaches such as Farmer Field Schools (FFS). Later versions of FFS moved away from the overreliance on intervention thresholds to include agro-biodiversity notions in their curricula. Farmer 'zoos' were established to show the different ecosystem functions, from herbivory to predation and biological control by parasitoids. However, FFS had a major drawback: their price tag. Hence, they were only successful for the limited time frame of the project funding them. Also, in some socio-cultural settings, the participation of women in formal training sessions such as FFS was not acceptable, yet women were at the frontline in some of the plant health and post-harvest activities (Chapter 15).

The success of any IPM endeavour relies heavily on giving quality training to farmers, and this can be an additional obstacle because of the scarcity of skilled trainers in national extension systems who can carry out such functions. Alternatives exist, for example by piggybacking on development projects and grass-roots NGOs, but their interventions are often limited by financial and timeline constraints. Today, with the advent of cheap and stable internet connectivity even in rural areas in Africa, IPM is about to be re-branded into 'precision IPM' and relies on modern ICT tools, including smartphone-based decision making and information exchange, for its deployment and large-scale dissemination (Chapters 10 and 15).

One particular case, cocoa in West Africa (Chapter 12), highlights the need for better harmonization between the good intentions of the industry to preserve the rainforest (e.g. Rainforest Alliance), and the reality of implementing plant health measures on the ground. In fact, shaded cocoa as in a rainforest needs more pesticide applications (against black pod and mirids), while opening the canopies would lower the use of fungicides by small-scale farmers and make the system more sustainable. The question remains, what can be done to approach these kinds of trade-offs in IPM.

3.6.3 The way ahead

We argue that a paradigm shift is needed for IPM to succeed in the future. In our vision, IPM 2.0 is primarily a science-guided decision-making support platform that (1) can reach low-literacy farmers with a customized, gender-targeted message in their own language, empowering them to take the right decision about pest management at the right time by using modern and affordable ICT tools; (2) is based on ecological principles regulating pest populations by promoting biodiversity that is essential for ecosystem function, as for example against banana diseases, banana nematodes (Chapter 9), cowpea insect pests (Chapter 10), cassava root scale (Chapter 6); (3) is supported by next-generation genomics tools to understand pest (meta-)populations (Agunbiade et al., 2014), with their interacting populations of endosymbionts (Brinkmann et al., 2008), as well as populations of arthropod and microbial antagonists (Pierce et al., 2014); (4) promotes resistant/tolerant varieties and enhanced agro-ecosystem resilience (Willis et al., 2018); (5) advocates the use of biopesticides (based on plant extracts and/or entomopathogenic microorganisms) if the pest populations get out of ecological balance (Chapter 13); and (6) insists on using healthy seed and good planting materials (Chapter 15). As mentioned earlier, safe use of insecticides can be considered *as the last resort* (Jepson et al., 2014).

The IITA plant health team will implement this new 'precision IPM' paradigm to manage the recent invader, the FAW, in Africa (Chapters 4 and 7). One of the challenges will be to uncover the vast unknowns about this pest in its new territory, particularly with regard to its interactions with the natural vegetation, for example during the off-season when cultivated cereals are not available. The importance of trees for enhancing ecosystem services will also have to be considered (Kuyah et al., 2016), as suspected for *Striga* control (Chapter 14). Other ecosystem functions of natural vegetation are the hosting of (indigenous and introduced) biocontrol agents during the off-season when the main crop is not present, as in the case for maize and cowpea (Chapters 7 and 10), and which is expected to apply also for FAW. One option that is currently put forward for FAW control is the use of GM maize, which is much more compatible with biocontrol than synthetic pesticides (Bale et al., 2008). However, as already discussed in the section on resistant varieties, the challenges for deploying GMOs in Africa remain considerable at technical, institutional and policy levels.

One of the critical issues for efficient FAW management is the detection of early life stages – egg masses and young caterpillars – which are more vulnerable to the application of biorationals, and also better exposed. Our proposal to address this issue is to further improve the Farming Interface App, co-developed by IITA and partners at the Michigan State University (Chapter 10), for (1) guiding farmers scouting in their own field for detecting early infestations, (2) empowering them to take real-time decisions about pest management, (3) feeding back to the VIPS expert system, developed by NIBIO (2018), real-time data on crop phenology, performance, pest occurrence and severity for improving the accuracy of VIPS predictions at local and landscape level. This tool has been deployed in several countries across the world, is scale neutral, that is it can be successfully deployed at the smallholder household level in the village as well as by large commercial farms, but needs to be tailored to local circumstances. Communication and sensitization campaigns that take advantage of such modern ICT tools for better farmer involvement will go a long way towards the implementation of research results beyond the end of the project, which must already include their substantial costs. They are expected to reach and impact far more farmers than traditional FFS. At the moment, commercialization of IPM advice seems, however, out of reach in most African countries.

4 Overall assessment

Among the 58 projects assessed when writing this book, 40 projects were implemented in field situations and covered a large area (importance of project 2–5). Among all projects, 20.7% had a major contribution (>50%) from biological control, 24.1% from resistant varieties, 34.5% were based on cultural manipulations, 8.6% derived their success from biorational control and in 12.1% no technique predominated. Modest chemical control measures were taken in 25.9% of all projects, but were never a major component (contributing between 10% and 20% to the total success). While 18 projects employed only one technology, 40 (69.0%) used more than one. In predominantly biological control projects, 40% were tested in the field and adopted by farmers; for resistant varieties, the corresponding figure was 31%, and those for cultural control measures 35%. This means, across the institute, a good third of all projects delivered technologies that were adopted by farmers. One-third of all technologies, though tested, remained to be widely used, and one-third were academic studies, which formed the scientific basis for developing novel approaches in plant health. Bigger projects achieved higher impacts when biological control or resistant varieties were the main technologies; for cultural practices no relation between input and impact was found.

These numbers show that investments from donors in breeding and biological control offer good success rates, and hence should guide donors in their decision making on where and how to invest their limited resources for maximum outcome and impact. There is no doubt about IITA's impact in genetic improvement and biological control for better plant health (= increased yield for farmers); however, due to complicated and location-specific combinations of interventions, the impact of cultural control and IPM measures is quite difficult to assess and is therefore often neglected even by our collaborators (Ainembabazi et al., 2018). And often the origin of varieties is not known or successful biological control is not observed, as exemplified by the cover image (Fig. 2). It shows a female *Therophilus javanus* searching to oviposit into a *Maruca vitrata* larva on an infested cowpea pod. This parasitoid has been imported from Asia into Africa, mass reared at IITA and successfully established (Chapter 10). It is a perfect example of one of these contributions, in this case biological control, that go mostly unobserved by farmers and extension officers alike.

In general, IITA was promoting IPM that was based on research outputs beyond mere insecticide management. The projects demonstrate the practical implementation of sustainable IPM measures aiming at high productivity in the difficult African situation, though without fulfilling the stringent requirements of European 'organic' agriculture.

In Africa, agricultural production has so far largely been organic by default, due to farmers' lack of resources to buy or even have access to synthetic pesticides and other inputs. This, however, applies only to staple crops. In cash crops, overuse, misuse and abuse of synthetic pesticides are evident and likely increasing. Half-hearted attempts at introducing IPM in the form of pesticide management thereby only tend to perennially install and guarantee further insecticide use.

Environmental and health-related pesticide-induced problems are real, but not sufficiently addressed in most African countries. Likewise, many African

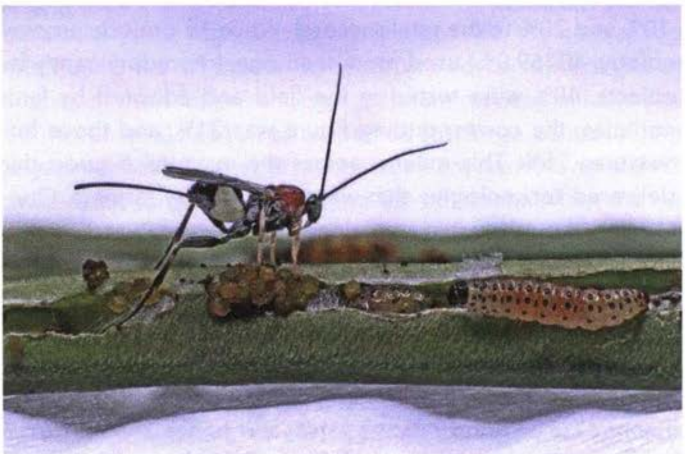

Figure 2 *Therophilus javanus* parasitizing *Maruca vitrata*. Photograph by Georg Goergen.

Published by Burleigh Dodds Science Publishing Limited, 2019.

countries have pesticide legislation in place, but there is no enforcement, therefore inappropriate sale and use of synthetic pesticides are not a concern. Only produce exported to Europe and abroad is analysed for pesticide residues, whereupon pesticide practices are adjusted accordingly to fulfil the requirements of the importing countries. There is still major work to be done in Africa in awareness creation and capacity building to address this problem (Chapters 3 and 15).

Globally, insecticide-free vegetable production relies on a series of biocontrol programmes (see European glasshouses: van Lenteren, 2000). At present this is, however, almost impossible to repeat under African field situations, though certainly a worthy long-term goal. Certified 'organic farming' is known only in some highly particular socio-economic environments in East and South Africa. Flower producers, for instance, could benefit from the well-established biocontrol programmes of European glasshouses. Presently, even producers of the so-called fair-trade products seem to ignore the opportunity to reduce risks to their workers and the environment, as documented by high residues of cocktails of insecticides in their produce (Roseth, 2010). Unfortunately, there is no incentive to change practice in Africa since importing countries do not ask for minimum levels of pesticide residues in non-food plants.

Particularly in weed control, eco-friendly IPM solutions often ask for more labour by the farmer, who - once the project is over - might not profit anymore from side benefits of the project. Unfortunately, IITA and its sister institutes have no means of pushing for implementation once financial support ceases, while sales people of chemical companies will continue to effectively peddle their wares, irrespective of the research results that usually aim at curbing pesticide abuse. Again, better education at all levels about long-term benefits of environment-friendly solutions is absolutely needed.

Further opportunities to reduce the use of synthetic pesticides as well as the burden of farmers in pest control are offered by exploiting insect-plant interactions. Surveillance and monitoring with pheromone traps, combined with prognosis and forecasting models and ICT tools, should be part of the future IPM strategy for Africa. The much-promoted push-pull technique exploits this avenue (Pickett et al., 2014), but is highly situation-specific. More research is needed on chemical ecology on both indigenous and alien pests, on crop varieties used in Africa and under African field conditions to further harvest the benefits of this technology.

5 IITA's plans for the future

While traditional farming systems with long fallow periods are sustainable, they need to become more productive. In most aspects, African agriculture still is organic farming, a benefit that should not be lost by repeating all mistakes (pesticide treadmill) of other continents (Chapter 2). For IITA, organic farming in the context of IPM is not a dogma; we rely on scientific evidence to provide a diversified, productive agro-ecological system (Frison et al., 2011) with the aim to make ecosystems resilient (Willis et al., 2018). This can only be done in close collaboration with other national and international organizations.

IT-based solutions to help farmers and extension services to improve plant protection practices in real time has become and will become more important in the future (Chapters 10 and 15). IITA is very much involved in what we could call the beginning of a plant protection revolution in Africa. New ICT tools, combined with the 'old' professional expertise such as taxonomy (morphological and DNA based), insect behaviour studies, phenology studies, agro-ecological knowledge and more, carve out a new area that can completely change future IPM strategies for many crops in Africa. IITA is presently in the forefront of developing ICT tools to help countries survey the spread of new pests and diseases, develop pest diagnostic tools and phenological models for prognosis and forecasting of pest outbreaks for broadcasting through different channels. Presently, we may not be able to provide country- or region-wide simulation modelling that is as precise as we would like, mainly due to the general lack of up-to-date and adequate networks of meteorological stations in most of Africa. Satellite data can partly compensate for lack of detailed data. These hindrances should not stop Africa from taking part in the possibilities that new ICT tools offer to farmers when and where they need them.

IITA is in agreement with much of the UN-commissioned IAASTD report (IAASTD, 2012), but not in its statements concerning pesticides and GMOs (as well as inorganic fertilizer) (see also Chapter 2). IITA supports the Malabo Declaration (2017) and will pragmatically develop solutions and demonstrate what works under local circumstances, by rallying African colleagues of universities, other research institutions and farming associations around a common goal for gradual change in legislation. IITA is an efficient actor situated between universities and implementing NGOs and government agencies. Unfortunately, national programmes, the original partners in research, who are supposed to pick up, adopt and adapt the results, often have no funding for scaling. This asks for better support to NARS partners, which in a project-based institute like IITA becomes difficult, but needs to be tackled.

Our direct and most successful clients often manage large farms with high inputs. They are well prepared to benefit from research results. The vast majority of farmers run, however, small subsistence farms. If IITA wants to increase its impact its projects have to cater to these clients too by facilitating access to cheap technology and education also to the young and to women, for instance by promoting youth entrepreneurs to address also production of biological control agents and biopesticides at local and national levels.

In Chapter 1, one of our partners recommended 'that IITA moves more decisively towards a holistic agro-ecology framework and away from a reductionist approach prioritizing short-term solutions such as GMOs, pesticides and synthetic fertilisers'. This book should provide concrete answers to this recommendation and demonstrate that we do not favour pesticides or GMOs. What we can certainly do better is communicating to the research community and the public in general about our strategy, which is solidly anchored in science-driven pest management, prioritizing biological control, resistant varieties and biorationals whenever possible. We suspect the above comment stems from the fact that we are certainly successful in publishing in indexed journals, but poor when it comes to 'making noise' about our successes, for example in the media, and more recently, necessarily, the social media. Our 2012–20 refreshed strategy clearly spells out the ecological base of our plant health approach, but evidently this is not the kind of information the general public is expecting to read. Otherwise our colleagues would possibly have noted that the IITA plant health team is far from prioritizing the mentioned short-term solutions.

In the refreshed IITA strategy 2012–20, three performance indicators are key, namely (1) lifting 7.2 million Africans out of poverty, (2) restoring 7 500 000 ha of degraded land and (3) increasing the yield of IITA's mandate crops by 60%. It is of course difficult to distinguish which factors (new varieties, plant health interventions, fertilizer and soil improvement techniques, inclusion of women, etc.) have contributed most towards the institute's overall achievements or impact, because they are all interdependent of each other. For instance, the potential genetic gain from a good variety can only be realized if seeds are healthy, the soil is not degraded, water and nutrition are optimal, but also if the social context allows its deployment. Whether this in turn leads to poverty reduction also relies on post-harvest technologies, access to market and whether increased profit benefits the family in need. As shown in this volume, improved plant health management interacts with most of these factors and is one of the key components contributing to the overall success in partly or fully achieving these targets by 2022. This was also recognized by the independent committee selecting IITA as the winner of the Africa Food Prize 2018.

How well then have IITA's responses to the triple challenge to agriculture across the world been met?

1 Feed more people on the same land: IITA's achievements clearly contribute to this goal.
2 Mitigate climate change: our classical biocontrol, smarter insecticides, resistant varieties (particularly if produced in Africa), less energy-hungry weed control, agroforestry measures clearly contribute.

3 Protect biodiversity: biocontrol implementation inherently supports this agenda. Recent biodiversity studies across all taxa by the biodiversity centre and its attached research forests broaden the approach.

6 Recommendations

- Raise awareness within the CGIAR, the broader donor community and African governments that single classical biological control projects against invasive alien species can produce benefits as high as complete multi-year breeding programmes, but require corresponding capacity building.
- Improve taxonomic capacities sustainably in collaboration with CAB International for foreign exploration and attribute a similar status to non-plant genetic resources as to plant genetic resources.
- Promote the biodiversity centre to teach citizens about the value of biodiversity, which can only survive if protected by the citizens.
- Support basic studies to understand the systems in collaboration with universities across the globe, favouring studies on competitive displacement, dispersal, food webs, alternative hosts and ecological niches, behaviour (particularly of ovipositing females) and tri-trophic interactions.
- Support horizon scanning and early warning systems for rapid response to emerging biological risks in collaboration with the Inter-African Phytosanitary Council of the African Union.
- Support holistic plant breeding approaches that also aim to breed for synergistic effects between varieties and natural enemies (instead of favouring some pests indirectly and unwillingly due to antagonistic effects).
- Develop and promote sustainable and cheap soil improvement practices that target weed and pest control without increasing labour demand, by developing sustainable IPM interventions and alternative products so that obsolete synthetic pesticides and herbicides like glyphosate become farmers' last choice.
- Strengthen collaboration with the private bio-pesticide industry, possibly through innovative forms of partnerships and financial co-investments. Make industry aware that biorationals can be as efficient as chemical pesticides, and often cheaper in production, while keeping profit margins.
- Develop IT-based solutions to help farmers and extension services to improve plant protection practices in real time by combining traditional IPM with modern ICT tools - including artificial intelligence - and climate modelling to develop 'precision IPM'.
- Evaluate the economic, environmental and health impacts of all projects 5 years after their closing in collaboration with major donors.

- Publicize better sustainable and environment-friendly techniques, based on impact assessment of all plant protection measures in order to discourage farmers to use cheap and seemingly easy-to-use pesticides.
- Support NARS for scaling up IPM technologies, including production of biological control agents and biopesticides by youth entrepreneurs.

7 Acknowledgements

We thank all donors of the mentioned projects. Without their support our work would not have been possible (major donors are listed in the contents pages). We are also grateful to all contributors to this book, which was a huge communal enterprise and lists achievements that no single author could have assembled. We thank our colleagues in national and international organizations, without whose collaboration through the last 50 years IITA could not exist. Recently, this work has been partly coordinated in the CGIAR Research Projects listed separately. And finally we thank the staff of Burleigh Dodds Scientific Publishing for their untiring support and encouragement.

8 Where to look for further information

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