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How does IPM 3.0 look like (and why do we need it in Africa)?

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The concept of Integrated Pest Management (IPM) was introduced sixty years ago to curb the overuse of agricultural pesticides, whereby its simplest version (IPM 1.0) was aiming at reducing the frequency of applications. Gradually, agro-ecological principles, such as biological control and habitat management, were included in IPM 2.0. However, throughout this time, smallholder farmers did not improve their decision-making skills and continue to use hazardous pesticides as their first control option. We are therefore proposing a new paradigm — IPM 3.0 — anchored on 3 pillars: 1) real-time farmer access to decision-making, 2) pest-management options relying on science-driven and nature-based approaches, and 3) the integration of genomic approaches, biopesticides, and habitat-management practices. We are convinced that this new paradigm based on technological advances, involvement of youth, gender-responsiveness, and climate resilience will be a game changer. However, this can only become effective through redeployment of public funding and stronger policy support.

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Introduction

We would like to start with some practical considerations demonstrating why our integrated pest-management concept should be labeled ‘IPM 3.0’. The past sixty years of Integrated Pest Management (IPM) have been well-described and characterized in detail [1••] with the following simplified historical perspective of IPM. Accordingly, the label IPM 1.0 is attributed to the initial efforts in the 1960s and 1970s for drastically reducing the indiscriminate use of pesticides by introducing the notion of threshold-based intervention derived from scouting. For low-literacy farmers in most developing countries, this was a novel and knowledge-intensive concept, which eventually required the introduction of educational-support systems such as the farmer field school (FFS). FFS became a useful approach to teach farmers basic concepts of agro-ecological principles throughout the cropping season though chemical pesticides remained the mainstay of pest-control interventions [2]

During the last 20 years, in the attempt to further minimize the application of chemical pesticides, the IPM approach was broadened by increasing the range of nature-based solutions — often limited to biological control — with improved agro-ecological interventions such as planting companion flower banks and other ecological engineering measures to increase the presence and efficacy of biological control agents [3••]. To popularize these fairly complex management approaches involving multitrophic interactions, sometimes across landscapes, the same authors developed successful mass-media campaigns using rural radios and TV shows. These efforts were pioneered in Vietnam, and in some instances, pesticide applications in rice (*Oryza sativa*) were reduced by up to 60% [4]. Around the same time, the first versions of the ‘push–pull’ concept were developed for maize (*Zea mays*) in Kenya to exploit plant volatiles attracting pests to nonhosts at the field border, as well as repelling them by companion plants inside the field [5]. This new, improved version of IPM is considered an important upgrade of the previous IPM 1.0 approach and can hence be tagged as IPM 2.0, although this label had already been used in 2013 in conjunction with plant pathology on a special occasion, the 10th Conference of European Foundation for Plant Pathology [6]. We further consider the agro-ecological crop-protection concept proposed by [1••] as one of the most advanced forms of IPM 2.0.

If just a fraction of smallholder farmers in tropical Africa would implement IPM 2.0 in their fields, we would certainly eliminate a lot of unnecessary pesticide applications. However, this is still insufficient, particularly in view of the challenges facing the next generations of farmers who have to manage pests in a sustainable, climate-resilient, and biodiversity-supporting manner. Hence, the IPM 3.0 concept we are proposing here goes a step further 1) by adding a more proactive farmer empowerment and educational component, both for pest diagnosis and control, 2) by insisting on investigating the real causes of a pest problem instead of contenting to treat the observed symptoms in reactive mode, and 3) by integrating all compatible innovations to provide synergistic pest prevention and control interventions, while keeping chemical pesticides as the option of last resort to save a harvest that would otherwise be totally compromised. This enhanced version of IPM based on the above three pillars, illustrated in Figures 1–4, provides practical recommendations that can be implemented with little additional resources.

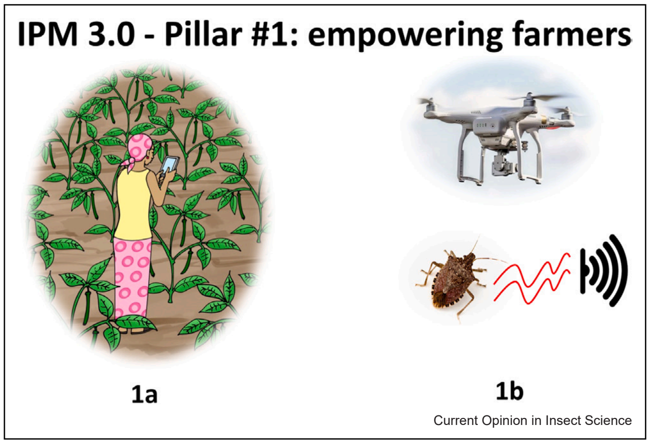
Pillar #1: what does it take to empower smallholder farmers to make their own decisions in sustainable pest management?

In most of tropical Africa, farmers' decision to spray their crops is still either calendar-based or triggered by visual and conspicuous pest-attack symptoms. This practice has led to indiscriminate use of synthetic pesticides, with their adverse side effects on human, animal, and environmental health [7••]. In recent years, this trend has been exacerbated by the perceived impacts of climate disturbances, whereby farmers increase the use of pesticides as an adaptive response to mitigate pest-induced yield losses [8•].

During previous versions of IPM, attempts to curb this trend have relied on several farmer- training approaches, of which FFS has been widely practiced in tropical Africa. The FFS approach teaches farmers basic principles of agro-ecosystem analysis, with the ultimate goal to make the farmer recognize pests and their damage symptoms in the field and understand when the damage threshold is attained in order to intervene. However, FFS requires a season-long attendance by farmers and trainers organized in small groups, which is resource-intensive and can only reach a small percentage of farmers [9]. Today, most farmers continue to face 1) the widespread lack of appropriate tools to enable them to take informed decisions, 2) limited access to alternatives to harmful pesticides, compounded by 3) the limited availability of personal protective equipment.

Another frequent obstacle to farmer empowerment in decision-making is the lack of proper identification of pest organisms, particularly the damage-inducing life stages. The invasion of the fall armyworm (*Spodoptera frugiperda*) into Africa provides one of the most flagrant examples. This pest species was totally new to maize farmers, with no other indigenous insect pest producing a similar damage pattern. So, maize farmers became aware of the pest attack only when they saw heavy damage. At that point, either the crop yield was already compromised or, depending on agro-ecological/climatic conditions, the plant was able to outgrow the attack and recover with minimal yield loss [10]. In both cases, pesticide applications were too late to produce an effect on yield: they were just an unnecessary cost and burden to the environment. It is evident that farmers were not aware of the early stages (egg masses and young instars) that started the infestation, an observation that provides an entry point for farmer education/empowerment [11]

Figure 1

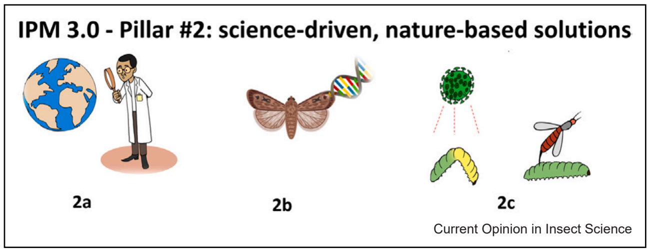


Simplified representation of pillar#1 for IPM 3.0. The farmer uses a digital advisory on her smartphone to acquire essential information about the plant health status of her crops (ranging from manual input to artificial intelligence) **(1a)** and linked to external environmental monitors such as UAVs and nanosensors for additional real-time data capture **(1b)**.

Recent research advances provide accurate insect-pest diagnostics by using artificial intelligence [12••,13••,14] in conjunction with automatic monitoring tools [15•] and nanosensors (such as gas nanosensors for pheromone detection, Figure 1b) [16•]. These tools assist farmers in properly diagnosing pest problems on their own farms and are the appropriate innovations in a forward-looking IPM 3.0. Once these powerful tools are made accessible to smallholder farmers taking advantage of increasing use of smartphones and availability of Internet in rural areas, they will be operationalized at the farm level and provide a high level of accuracy in pest identification.

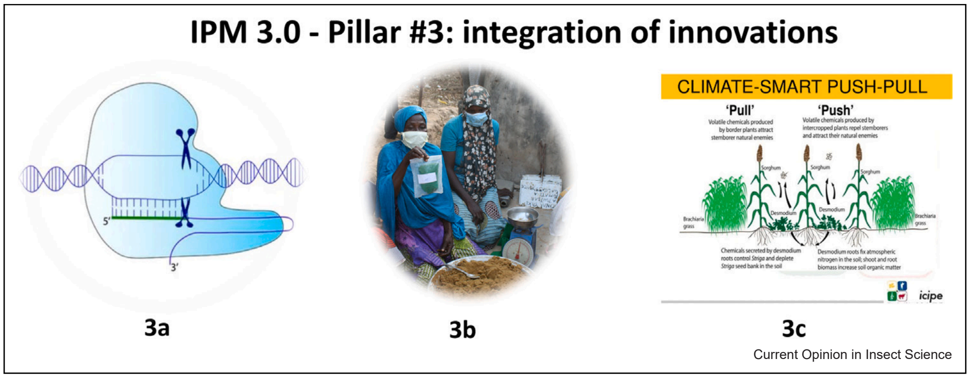
In the meantime, smallholder farmers should not be left unaided when confronted with the risk of new invasive pests (on top of the current ones), while at the same time being unable to discern control recommendations given by peer farmers or unskilled pesticide resellers who

Figure 2



Simplified representation of pillar#2 for IPM 3.0. R4D studies investigate the biodiversity of pests and related natural enemies **(2a)**, complemented by population genetic studies **(2b)** and by the assessment of the diversity and efficiency of natural enemies such as entomopathogenic organisms and parasitic wasps **(2c)**.

Figure 3



Simplified representation of pillar#3 for IPM 3.0. Technological innovations ready for integration into the IPM 3.0 framework: novel genomic tools such as CRISPR–Cas9 **(3a)** biopesticides exemplified by locally produced neem-powder sachets in Niger **(3b)**, enhanced habitat-management approaches such as the *icipe* push–pull approach.

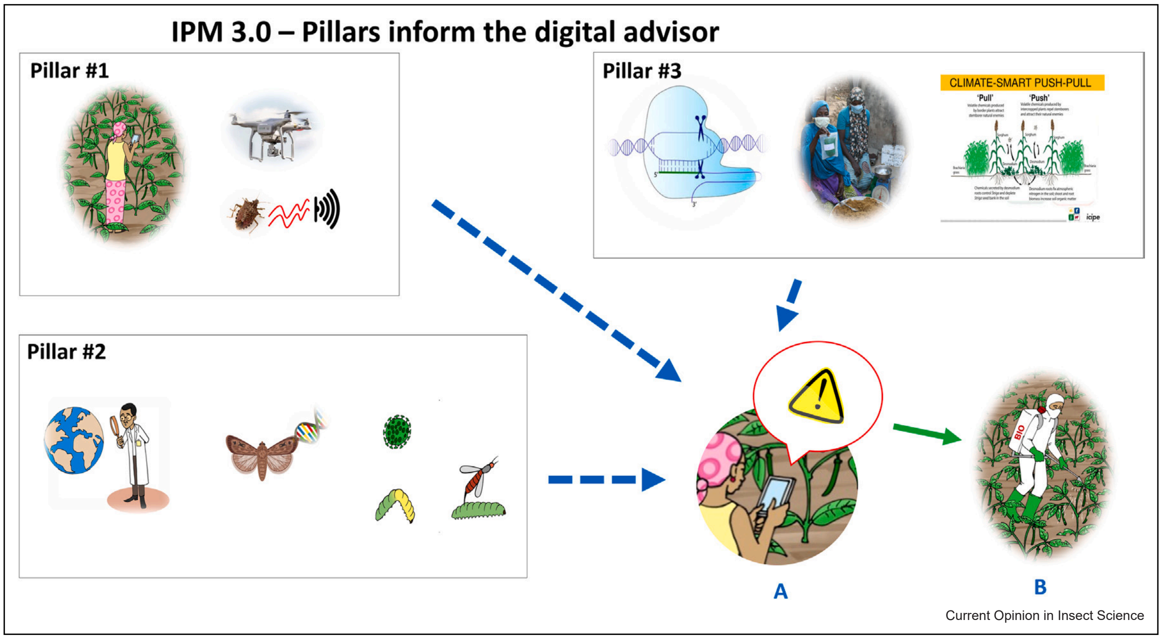
often offer for sale unsafe and inefficient synthetic pesticides [17]. Some progress in educating and empowering farmers to take the appropriate decisions has already been achieved by simple apps such as the Farmer Interface Application (FIA) developed by a consortium headed by the International Institute of Tropical Agriculture IITA (Cotonou, Benin) together with the Norwegian Institute of Bioeconomy Research NIBIO (Ås, Norway) with funding from the Norwegian Agency for Development Cooperation NORAD (Oslo, Norway). This app was validated for *S. frugiperda*, and advanced versions are now being fine-tuned for cowpea (*Vigna unguiculata*) pests. The current version of FIA assists farmers in recognizing early stages of the pest and scouts the field in a random manner guided by Global Positioning System GPS coordinates in order to determine an intervention threshold [18].

By incorporating animation videos to guide low-literacy users through the different functions of the app, and at the same time make use of voice recognition and commands (for now in French, but new versions in two main local languages in West Africa are about to be released soon), simple digital advisories such as FIA are designed to address the needs of all gender and social groups: they thus reduce inequalities instead of further exacerbating them. This is particularly relevant in parts of sub-Saharan Africa where women are still coping with cultural barriers that prevent them from, for instance, sitting down with men for training sessions by extension services [19•].

Pillar #2: pest- and disease-management approaches anchored in science-based ecological control

Once IPM 3.0 becomes operational and equips smallholder farmers with powerful and user-friendly diagnostic and scouting tools together with pest-management advisories, its success will still depend on the quality of the available solutions. Regardless of the improved diagnostic power, farmers will carry on treating the symptoms of a problem in their own fields while the true cause might be somewhere else. Often, an organism develops into a pest simply because of ecological

Figure 4



Integration of the three pillars into the digital advisory to produce pest-management recommendations. The information generated by the 3 pillars is integrated into the digital advisory, who provides the farmer with plant health recommendations **(a)**. If preventive control is deemed insufficient to keep the pest under a damage threshold, the advisory will formulate recommendation to apply a range of efficient biopesticides **(b)**, and keeping chemical control as the *solution of last resort*.

imbalances, climate change, or merely because of its invasive nature.

One of the most recent examples illustrating how such a puzzle was cracked, thanks to long years of international collaboration across continents, is that of the legume pod borer *Maruca vitrata*. In Africa, this pest has been tacitly regarded as indigenous, and after years of unsuccessful efforts in finding resistance in cowpea, a transgenic approach using the Cry1Ab *Bt* gene was eventually able to provide efficient control [20]. However, concurrent biodiversity studies revealed substantially different guilds of hymenopterous parasitoids in Africa and tropical Asia. The lack of specific parasitoids in West Africa was particularly intriguing [21], indicating a potential for redistribution of biological control agents [22]. Meanwhile, population genetic studies indicated tropical Asia as the most plausible origin of the pest, thereby calling for an experimental assessment of the Asian biological control candidates in the African context [23]. In-depth biological studies were then undertaken to assess the host-specificity and maternal factors determining the potential of various biological control candidates, and particularly the braconids *Liragathis javana* and *Phanerotoma syleptae* [24]. These two hymenopteran parasitoids have been released experimentally in various countries in West Africa, leading to reductions of the pest population by up to 86% at pilot-release areas [25]. They are currently being released in biological control campaigns in Benin, Burkina Faso, Ghana, Niger, and Nigeria. The example of *M. vitrata* highlights the importance of challenging the pest status of organisms that seem to have only poorly adapted natural enemies in a given agro-ecology. A similar case study is that of biological control efforts against the diamondback moth *Plutella xylostella*. Host plant and parasitoid-diversity studies in South Africa revealed that *P. xylostella* might originate from this area [26], and this information has been used in several attempts to introduce biological control agents to other regions. This example has been reviewed in detail [27,28] and has provided the basis for the establishment and successful control of *P. xylostella*, for example, in eastern and southeastern Kenya (Kitui, Mwingi/Yatta, and Loitokitok areas) [29]. Both examples, however, clearly indicate that biological control alone will not provide a silver-bullet solution, and that it will need to be integrated with other compatible measures as illustrated in the next section.

Pillar #3: the integration of advanced genomic approaches, efficient biopesticides, and enhanced habitat-management practices

Over the past few years, the quest for sustainable pest-control solutions has seen the development of impactful innovations such as novel genomic tools, biopesticides, and ecological engineering. However, efforts to integrate these individual components into operational IPM schemes have not always been successful.

The last two decades of genomic approaches in breeding for insect-pest resistance have been mostly characterized by successes and failures in staying ahead of the race with pest organisms becoming resistant to *Bt*-gene constructs. However, more recent advances using the CRISPR–Cas9 technology present new avenues for improving crop resilience to pest attacks [30]. Thereby, the aim of this approach is not solely to improve plant resistance to biotic stresses, but also, for example, to modify plant signaling to attract natural enemies, specific parasitoids, as well as generalist predators [31]. Once these tactics get mainstreamed and properly integrated into a functional IPM framework as proposed by [32•], they will certainly contribute to optimizing biological control outcomes and reduce the application of unsuitable pesticides.

In Eastern and Southern Africa, potent biopesticides have been developed by the International Centre of Insect Physiology and Ecology (*icipe*, Nairobi, Kenya) and are now getting into the hands of farmers, thanks to joint endeavors with an emerging private sector [33•]. The integrability of biopesticides in an IPM framework is defined by their degree of selectivity toward nontarget organisms, but generally they have much fewer negative impacts on beneficial insects (including pollinators) than synthetic pesticides [34]. In West Africa, biopesticides gained momentum some 30 years back with the development of Green Muscle (based on the entomopathogenic fungus *Metarhizium acridum*) against locusts and grasshoppers, however, this effort could not be sustained owing to the lack of innovative private initiatives to support their production and commercialization [35]. More recently in Niger, women cooperatives have initiated the commercial production of a ready-to-use biopesticide made of locally available neem-seed powder, which is packed into a small tissue bag, soaked in water overnight, with the resulting solution sprayed the next day on a range of crops. What is innovative here is not the product per se, but the way it is produced and commercialized, which allows to bypass the lack of uptake by the more formal private sector.

The third major technological breakthrough comes from renewed efforts to improve the push–pull approach, which were spurred by the invasion of *S. frugiperda* in East Africa. A first upgrade of the original version was described as climate-smart push–pull by including new and drought-resilient varieties of companion plants [36]. This concept was subsequently validated with success to manage *S. frugiperda* soon after its appearance in Kenya [37], then tested for its potential for integration in conservation agriculture [38] and fine-tuned for enhanced scaling and adoption by farmers [39••]. Meanwhile, the mechanisms underlying the regulation of *S. frugiperda* by companion plants have been reported in detail by [40]. The push–pull approach was also investigated for its contribution to improving soil ecosystem services through their positive effects on soil organic matter [41]. Hence, we can infer that the push–pull concept could be a model for integrating other compatible IPM components as described above. Meanwhile, the IPM framework has been expanded to consider both positive and negative interactions between pest-control approaches and pollinators in a systematic way, becoming a new paradigm of Integrated Pest and Pollinator Management (IPPM). It has been defined as a framework for co-management of ecosystem functions driven by pests, natural enemies, and pollinators [42••]. While push–pull works mainly at the field level, IPPM considers elements of landscape management, aligned with an IPM 3.0 vision, whose ultimate goal would be to design and deploy IPM solutions for whole landscapes [43].

Perspectives

Is IPM 3.0 the right solution to curb the pesticide treadmill in Africa?

Past efforts to involve farmers in decision-making for pest management have only yielded marginal successes, mostly at pilot sites [1••]. Since farmers' buy-in for IPM 3.0 is essential, we put particular emphasis on farmer education and empowerment as the first and most important pillar for our improved IPM strategy. We have enough evidence that smarter insect-pest management can entirely rely on nature-based solutions if deployed correctly and in the right context (as described above in pillars #2 and #3), reducing or avoiding the need for the use of synthetic pesticides [44•].

How do we transition from current practices to IPM 3.0

We strongly believe our vision for IPM based on technological advances, involvement of youth, gender-responsiveness, and climate resilience will be a game changer. The existing agricultural research and extension capacities alone, particularly with the current public funding levels in Africa, however, will not be able to achieve this transformation on their own. We therefore urge a shift in public funding to focus on the need for increased investments in plant health research instead of insisting in quick wins that can easily be achieved by, for example, scaling projects. Who — and with what kind of means — is going to fill the research pipeline to produce the needed plant health innovations for successful IPM implementation in Africa, to deliver impact in the next 10 years and beyond? We should learn from lessons elsewhere, how to create virtuous feedback loops for a diversified agriculture, instead of falling into pernicious feedback loops as described by [45]. For all this to be achieved, a much stronger policy support as proposed by [44•] will be critical. A first essential policy intervention would be the establishment and operationalization of a regional early warning network to deter and intercept invasive and emerging pests, whose data infrastructure will be coupled with information gathered through innovations proposed in pillar #1. This will allow to integrate horizon scanning and advanced diagnostics approaches for fine-tuning customized pest-management recommendation at landscape and regional scales.

The successful implementation of IPM 3.0 relies on the increased availability and uptake of alternatives to synthetic insecticides such as biopesticides. Therefore, we strongly advocate for an enabling policy framework that should include, among others, clear regulatory directives facilitating the registration and use of biopesticides and harmonizing the process at the regional level to avoid the hassle of having to register the same product in each country. These measures should be flanked by the strict enforcement of current rules regulating the use of chemical pesticide. Additional efforts should be made at national and regional levels to adhere to minimum pesticide-residue levels, by providing the necessary infrastructure for their routine verification through accredited laboratories. This will both satisfy the increasing urban consumer demand for healthy and safe agricultural products, while also providing additional incentives for the on-farm use of biopesticides. However, we do recognize these policy changes might take time as they would require prior individual country engagement and endorsement.

Editorial disclosure statement

Given his role as Guest Editor, Manuele Tamò had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Thomas Dubois.

Conflict of interest statement

All authors declare no conflict of interest.

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- • of special interest
- •• of outstanding interest

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This review critically examines how IPM has developed over time and assesses whether this concept has remained relevant. Among the major weaknesses observed, the most challenging ones are the inconsistencies between IPM concepts, practice, and policies, and the serious lack of basic understanding of its underlying ecological concepts by farmers, which deter them from proper implementation. It is also observed that most IPM intervention still rely on the use of synthetic pesticides, while little attention is given to nature-based solutions and to the ecological functioning of agroecosystems. The concept of Agroecological Crop Protection is proposed as a solution to effectively put agroecology to the service of plant health.

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This study demonstrates how ecological engineering through the design and management of human systems based on ecological principles can maximize ecosystem services and minimize external inputs in rice cropping. These new practices need to be socially acceptable and require shifts in social norms of farmers, thereby calling for reforms in pesticide marketing policies. An innovative entertainment education TV series was developed to reach wider audience for improving farmers' ecological literacy, shifting beliefs and practices.

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This study provides a broad perspective on the main trends regarding the use of pesticides in developing countries and their impacts on human health and food security. Information is provided on the challenges of controlling these hazardous substances, along with the extent to which pesticides banned within the European Union are exported to third countries. Several mitigation measures are proposed.

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To understand the role of adaptation practices in pesticide use and health risks, adaptive responses linked to climate change perceptions of Zimbabwean smallholder cotton farmers were investigated. The findings show that due to perceived climate change impacts, such as a shorter growing season, farmers were adopting a range of adaptive practices. These included changes in pest management practices, such as increasing pesticide spraying frequencies due to keeping ratoon crops, which were increasing farmers' overall pesticide use. Other practices, however, such as reducing cotton acreage and diversifying crops, resulting in transformational adaptation, suggest the existence of opportunities for decreasing overall pesticide use or totally eliminating pesticides from the farming system.

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This article summarizes recent developments in deep learning and computer vision to monitor insects and other invertebrates. It shows how deep learning tools can be applied to exceptionally large datasets to derive ecological information and discuss the challenges that lie ahead for the implementation of such solutions in entomology. This transformation will be facilitated through 1) validation of image-based taxonomic identification; 2) generation of sufficient training data; 3) development of public, curated reference databases; and 4) solutions to integrate deep learning and molecular tools.

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This article presents a new mobile application to automatically classify pests using a deep-learning solution for supporting specialists and farmers, utilizing faster region-based convolutional neural network (Faster R-CNN). The proposed Faster R-CNN showed accurate recognition results of 99.0% for all tested pest images. The proposed deep learning method outperforms other previous recognition methods, that is, Single Shot Multi-Box Detector MobileNet and traditional back propagation neural networks.

14. Liu J, Wang X: **Plant diseases and pests detection based on deep learning: a review**. *Plant Methods* 2021, **17**:22, https://doi.org/10.1186/s13007-021-00722-9

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This review presents the advances in sensing of natural infochemicals (ICs) including biochemical sensors mimicking the olfactory system, chemical sensors, and sensor arrays (e-noses). Several mathematical models used in integrated pest management to describe how ICs diffuse in the ambient air and how the structure of the odor plume affects the pest dynamics are also presented.

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This article contributes new empirical evidence and nuanced analysis on the gender difference in access to extension services and how this translates to observed differences in technology adoption and agricultural productivity. Data collected from more than 7500 households in four major regions in Ethiopia indicate that female heads of households and plot-managers are less likely to get extension services through various channels and less likely to access quality services than their male counterparts after controlling for other factors. Results highlight the need for stratified productivity models by gender and crop in future research. In terms of policy implication, results highlight the need to focus on quality of service and alternative channels of information, such as radio, to improve productivity.

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This paper addresses the need to formulate general principles for synergistically combining traditional and novel integrated pest management (IPM) actions to improve efforts for optimizing plant protection solutions. It presents a conceptual framework for a modern science of IPM, which may assist attempts to realize the full potential of IPM and reduce risks of deficiencies in the implementation of new policies and regulations.

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Biopesticides are effective and environmentally sustainable alternatives to synthetic pesticides. At the International Centre of Insect Physiology and Ecology (icipe), the Arthropod Pathology Unit (APU) was established for effective biopesticide research-for-development (R4D), underpinned by a large repository of arthropod pathogens, protocols for lab bioassays and field efficacy testing, and an effective public-private partnership to generate new biopesticide products. The focus of icipe's APU has gradually transformed from basic to applied research leading to innovative, commercial products. Further, research is aimed at integrating biopesticides not only with other integrated pest management (IPM) technologies but also with pollination services.

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This study presents results from the evaluation of the latest version of push-pull technology termed ‘third generation PPT’. This new version was developed to improve further resilience of the system to climate change, by identifying more adapted and suitable companion plants, and evaluate field performance and farmer opinions of this new version in comparison with the earlier version, climate smart PPT, and farmers' own practices of growing maize in controlling stemborers, FAW, and striga weeds. Results show that the new companion crops are more resilient to hot and dry conditions which are increasing rapidly in prevalence with climate change. This version therefore presents a better option to upscale the technology and meet different needs of farmers especially in arid and semi-arid conditions.

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This report explores how linking the frameworks of nature-based solutions, integrated pest management (IPM), and One Health can facilitate the design of climate-resilient plant health systems, with particular benefits for reduced pesticide use and exposure. Climate-smart approaches to IPM are proposed as a means to reduce emerging risks from pest insects, nematodes, weeds, and diseases under climate change. The road map for ‘climate-smart IPM’ outlines the types of support required for practical implementation, such as climate-informed advisory services, information and communication technology, and policy.

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