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Insect pests and integrated pest management techniques in grain legume cultivation

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1 Introduction

Cowpea, *Vigna unguiculata* (L.) Walp. (Leguminosae: Papilionaceae), is an important grain legume crop in the semi-arid and dry savannah areas of the tropics (Singh and van Emden, 1979). The grain is a major nutritional source of protein for about 200 million people in sub-Saharan Africa. Cowpea production is highest in the West African countries of Nigeria, Niger and Burkina Faso. Insect-feeding damage caused by over one hundred pest species comprises a major biotic constraint on field production and post-harvest grain storage (Cork et al., 2009), and can dramatically reduce yields for subsistence farmers in West Africa. The insect pests feed on and damage the cowpea at virtually every crop developmental stage; major species include the legume pod borer, *Maruca vitrata*

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Fabricius (Lepidoptera: Crambidae); the coreid pod bugs, *Clavigralla tomentosicollis* Stål (Hemiptera: Coreidae) and *Anoplocnemis curvipes* Fabricius (Hemiptera: Coreidae); the cowpea aphid, *Aphis craccivora* Koch (Hemiptera: Aphididae); and thrips, *Megalurothrips sjostedti* Trybom (Thysanoptera: Thripidae). The annual level of crop damage inflicted by these insect pests is estimated to be as high as 60–100% in the field (Singh et al., 1990).

Efforts to control these pests have remained a challenge. Despite decades of capacity building and educational efforts, the tenets of basic integrated pest management (IPM) are poorly implemented across sub-Saharan Africa. The control of cowpea pests still relies largely on the timely application of chemical insecticides, but the efficacy of this tactic remains variable because of evolving insect population resistances, which afford survival when exposed to one or more classes of insecticides (Ekesi, 1999). Also, the insecticides are prohibitively expensive, often counterfeit or simply otherwise unavailable to low-income farmers in West Africa, who are in most cases usually inadequately trained in their safe and effective use (Giga and Biscoe, 1989; Alghali, 1991; Bottenberg, 1995; Van Alebeek, 1996). Effective control of this insect pest complex and protection against yield loss in cowpea crops are likely to occur only subsequent to the development and successful implementation of IPM strategies.

IPM describes a pest control strategy whereby a variety of complementary approaches – for example, cultural control, biological control, pesticides and host plant resistance(s) – economically minimize the negative effects of pests on a given crop or cropping system (Oyewale and Bamaiyi, 2013). The goal of IPM is to suppress pest populations to below the economic injury level (EIL) using techniques that also minimize harm to the environment, including people. The UN's Food and Agriculture Organization (AGP, 2016 - http://www.fao.org/agriculture/crops/core-themes/theme/pests/ipm/en/) defines IPM as:

> The careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms.

Cowpea IPM programmes in West Africa will likely use a combination of locally produced biopesticides and/or conventional pesticides along with biological control agents and host plant resistance traits, for example, traditional breeding and biotechnologies such as marker-assisted breeding, genome-edited crops and genetic engineering (Wolt et al., 2016). Given the central role of smallholder farmers in cowpea production, it is also critical to understand their needs in order to facilitate and ensure successful implementation of any innovative IPM strategies. The creation and deployment of supporting educational content in local languages using scale-neutral approaches that will be appropriate for farmers of diverse literacy levels will then be crucial for the widespread adoption of improved IPM practices.

Although biocontrol agents, pesticides and both classical and biotechnology-based host plant resistance are all proven methods for controlling the pests of cultivated cowpea, increasing the basic understanding of pest population dynamics will better afford developing the most effective IPM strategies through combinations of the available approaches. Yet, the successful application of IPM strategies has remained elusive for cowpea insect pests in part due to (1) an overall lack of population demographic data, (2) the existence of cryptic species complexes within pest populations or among different populations of the same pests and (3) the seasonal migration patterns of some insects such as *M. vitrata*.

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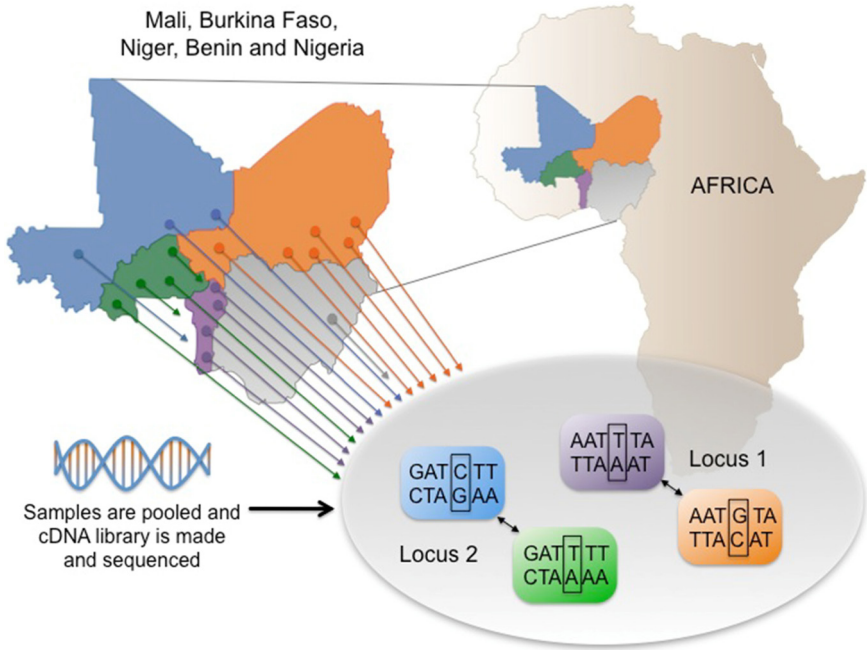


Figure 1 Hypothetical representation of the construction of a cDNA library by pooling insect samples from different cowpea-growing areas of West Africa (the arrows do not represent exact current sampling locations for any given insect species). The insects are selected from a diverse set of geographical locations, with mRNA pooled to create the cDNA library. Alignment of subsequent DNA sequence forms a set of expressed sequence tags potentially derived from the same locus and thus representative of alleles at a locus. The presence of polymorphisms among alleles in the form of SNPs can readily be adapted for genotyping individuals with high-throughput systems. Reprinted with permission from Agunbiade et al. (2012a).

These factors will continue to hinder any new application of control efforts against these pests if not taken into account. As such, IPM strategies are developed, refined and deployed to better characterize the life histories and population-level hierarchies of these insect pests in order to understand their relationships to the environment. To that end, we have developed a comprehensive toolset for the major pests of cowpea that combines traditional field studies with genomic techniques. This improved toolset enables the study of the population dynamics of cowpea pests (see Fig. 1 and 2) in order to craft those results into decision-making around the most effective control measure(s) for this complex of insect pests. This is outlined in the following section.

Population genetic tools can be used to determine the temporal and spatial distribution of pest insect populations and then leverage these insights for developing and deploying efficacious, cost-effective and environmentally sustainable strategies for controlling these pests (see Fig. 2 and 3). To date, the use of these tools has disclosed a more in-depth understanding of genetic diversity within *M. vitrata* populations (Margam et al., 2011b,c), and that *M. vitrata* living on cowpea have a great diversity of alternative host plants and common populations (Agunbiade et al., 2012b and 2014). From these results, the hypothesis that the

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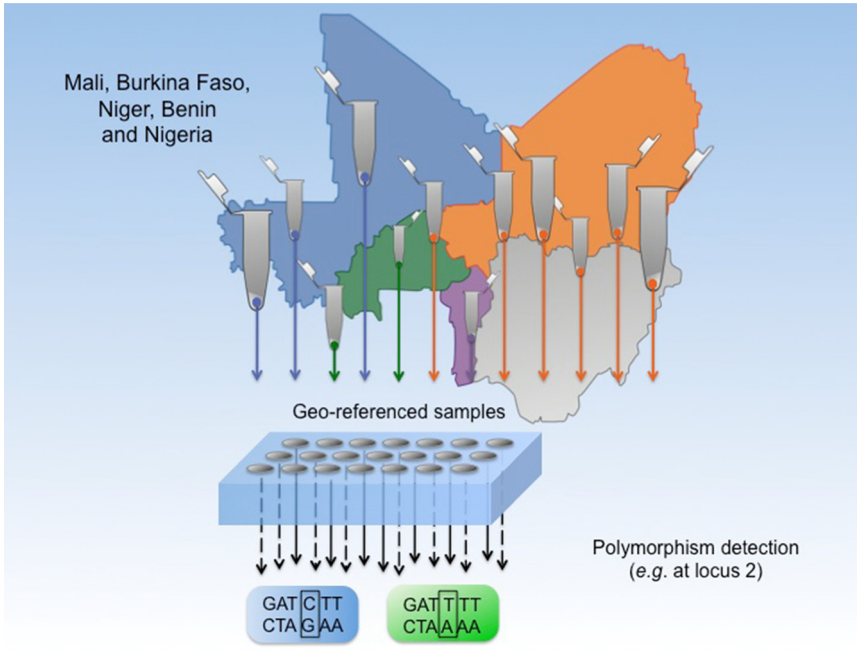


Figure 2 Representation of a hypothetical population genomics study in which individual insects from different locations (shown by the tubes) are collected from West Africa. Polymorphisms are detected among individual insect samples with high-throughput system(s) (shown as a blue plate) and are used to differentiate and correlate genotypes back to geographic locations, host plants, ecotype or other ecological characteristics described at the initial collection. Polymorphisms detected between individual insects are indicated as the C/G to T/A differences at the bottom of the figure. Reprinted with permission from Agunbiade et al. (2012a).

Maruca population living on cowpeas were interbreeding with *Maruca* on alternative hosts suggests that alternative host plants could likely act as a natural susceptible insect reservoir for transgenic cowpea expressing *Bacillus thuringiensis* (*Bt*) toxins. If so, then insects developing on natural refuge plants could serve as an overwhelming pool of susceptible individuals capable of mating with rarer, resistant individuals emerging from the transgenic crop.

Alternative host plants may also serve as a release point for biocontrol agents. Having developed a large transcriptome resource for *Megalurothrips sjostedti*, *Aphis craccivora*, *Clavigralla tomentosicollis* and *Anoplocnemis curvipes* that were used to detect polymorphisms among transcripts from the different populations (Agunbiade et al., 2013), this work potentially establishes a foundation for the future development of molecular markers and subsequent population dynamics studies within these insect populations. Use of such molecular tools may lead to the elucidation of biotypes that respond differently to host plant resistance traits, to the population structures of the pest populations or even to a better understanding of migratory patterns of the pests between wet and dry seasons.

To improve adoption and scalability of novel IPM technologies across West Africa, several important questions concerning the population of smallholder farmers must also

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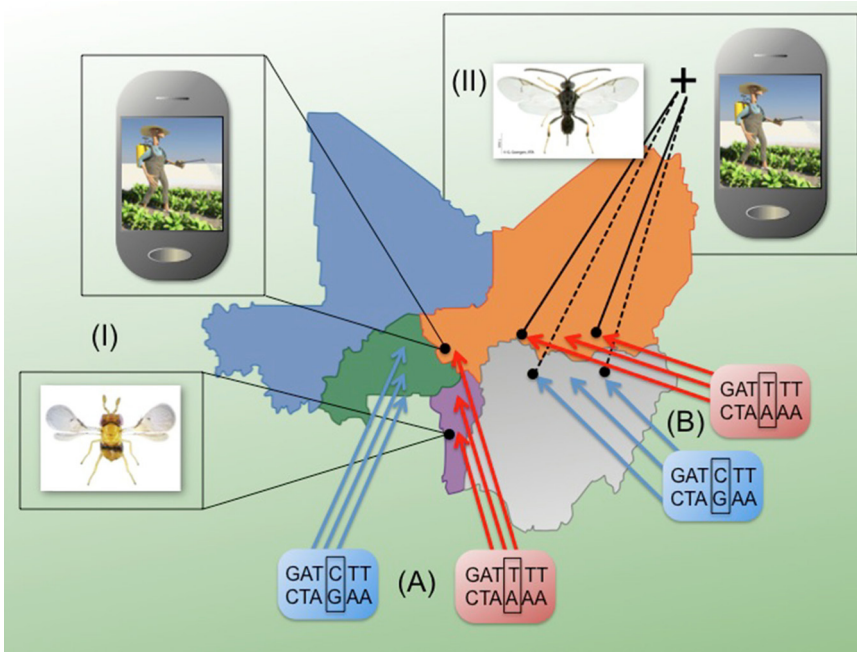


Figure 3 Hypothetical use of information gained from insect population genomic studies and how such information could be used in decisions associated with deployment of IPM strategies in two scenarios. In scenario A, the insects move from the south to the north in the rainy season, with biocontrol agents released in the south (in endemic regions) prior to migration for a long-term suppression of the pest population; temporary control measures (e.g. neem sprays) may be required in non-endemic regions if pest levels become too high. *Apanteles taragamae* is shown as an example of a biocontrol agent. In scenario B, the pest is endemic in both regions, with no significant longitudinal movement patterns. A possible pest control strategy in scenario B could involve the release of parasitoids (in both the south and north regions) along with implementation of an education programme concerning temporary control (e.g. with neem sprays) if pest levels become damaging. *Trichogrammatoidea eldanae* is shown as an example of a parasitoid. The farmer in the figure is applying a plant-based extract spray and thus does not require personal protection equipment; if a synthetic pesticide were used in this extension material, the farmer would have to be shown with personal protection equipment. Reprinted with permission from Agunbiade et al. (2012a).

be addressed; in particular, (a) What are the main drivers of farmers' pest control decisions? (b) Are farmers aware of the unintended negative health and environmental consequences that may be caused by persistent misuse of chemical pesticides? (c) What are the socio-economic characteristics of these smallholder farmers? and (d) How do farming systems compare across countries? We address these important questions by drawing not only on farmer survey results from Benin (Agyekum et al., 2016a) and Burkina Faso (Reyes et al., 2013) but also from insights from a choice experiment that sought to evaluate cowpea farmers' preferences for pest control options in Benin (Agyekum et al., 2016b).

Cowpea technologies developed by scientists, including novel control methods, can be utilized by low-resource farmers if the information is accessible to them. Thus, we

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have also collaborated with Scientific Animations Without Borders (SAWBO) to create educational animated videos specifically designed to serve individuals in highly multilingual African countries who have previously not had, or were not given adequate, access to the dominant, typically ex-colonial, national/administrative language in a given country. These educational videos can be transmitted from cell phone to cell phone via Bluetooth® technology, now widely available almost everywhere in Africa. To date, we have developed videos for improved cowpea production practices in West Africa, including solar drying, triple bagging of cowpea seeds to eliminate storage insect pests and the use of neem seed extract as a bioinsecticide against major insect pests of cowpea.

Developing and distributing insect pest control tactics that are accessible to indigenous populations is crucial for stabilizing food resources in many developing nations. Below, we outline specific research progress made towards enhancing cowpea IPM efforts in terms of both production and control of the pest complex. But it is by coupling these efforts to the development of novel video educational resources tailored in local languages that significant gains have already been made for improving the welfare of people across regions of West Africa. We term this coupled approach as 'precision-IPM'.

2 Known pest biology

2.1 Cowpea aphid (*Aphis craccivora*)

Aphis craccivora is a medium-sized, shiny black insect which feeds on the undersurface of young cowpea leaves, stem tissue and on pods of mature plants with a varied life cycle across Africa (Singh and Allen, 1980). An adult may live for 6–15 days and may produce more than one hundred progeny in its lifetime. They undergo incomplete metamorphosis (Whitworth and Ahmad, 2009) and reproduce both sexually and asexually (Trionnaire et al., 2008). The insect passes through four nymphal instars before reaching adulthood. Development time from the first instar to adulthood takes on average 3–5 days. Their typical annual life cycle is characterized by a succession of parthenogenetic generations and one sexual generation (Moran, 1992; Simon et al., 2002). A generation can be completed within 10–20 days. The growth, development, fecundity and longevity of *A. craccivora* varies with weather conditions, soil fertility, soil moisture and host plant (Ofuya, 1997). Winged adults are easily disseminated from one plant to another (Blackman and Eastop, 2008).

Damage to cowpea is caused by both adults and nymphs. Attacks cause plant stunting, leaf distortion, premature defoliation and the death of seedlings (Singh and Allen, 1980). They are known to cause significant damage even at low population densities due to the ability to transmit at least fourteen viruses (Rossel and Thottappilly, 1985; Thottapilly et al., 1990), including the cowpea aphid-borne virus (Raheja and Leleji, 1974; Atiri, 1984; Atiri et al., 1984, 1986, 1987; Atiri and Thottappilly, 1985). These viruses produce severe cowpea mottling, chlorosis and seed shrivelling, which can dramatically reduce yields.

2.2 Flower thrips (*Megalurothrips sjostedti*)

Adult thrips are shiny, black, minute insects that feed on the reproductive structures (flower buds and flowers) of cowpea. Infestations cause flower discolouration, distortion, abortion and abscission, thereby preventing pod formation, with estimated yield losses

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from 20–100% (Singh and Allen, 1980; Rusoke and Rubaihayo, 1994; Edema and Adipala, 1996). The entire life cycle takes 10–15 days (Alabi et al., 2004; Dabiré-Binso et al., 2008). Eggs are laid in the flower buds, and larvae feed voraciously on the plant, causing extensive damage (Singh and Allen, 1980). They have a rapid development, comprising the egg, two larval instars, prepupal, pupal, and adult stages. The larval stage is the most destructive. Pupation takes place in the soil. Males are haploid, and are produced only by unfertilized eggs, while females are diploid.

2.3 Legume pod borer (*Maruca vitrata*)

Maruca vitrata is endemic in all cowpea-growing regions of West Africa (Jackai and Adalla, 1997; Baoua et al., 2011; Ba et al., 2009). It is one of the most serious pests of cowpea due to its extensive host range, high damage potential and cosmopolitan distribution (Taylor, 1967; Raheja, 1974; Katayama and Suzuki, 1984; Ke et al., 1985; Sharma et al., 1999). Being a nocturnal insect, females fly at night and deposit eggs singly or in batches of two to six on flower buds, vegetative buds, flowers and leaf axils (Taylor, 1967, 1978; Traoré et al., 2013). Eggs hatch in about five days. The larvae undergo five larval developmental stages. The larvae are very active and tend to fall off the webbed flowers and pods with the slightest disturbance, by spinning a silken thread. The larvae feed on flowers, stems, peduncles and pods of cowpea, thereby causing damage at all developmental stages from seedling to podding stages (Singh and Taylor, 1978). However, the greatest damage occurs at flowering (Singh and Jackai, 1988). The larval stage is the most destructive one, causing yield losses of as much as 80% (Singh et al., 1990) depending on location, management and the cultural practices employed. The prepupal period lasts for 2 days. Pupation occurs in a silken cocoon among webbed leaves/pods or in the soil. The life cycle is completed in 18–35 days (Taylor, 1967; Akinfenwa, 1975). During the rainy season, *M. vitrata* population overlaps on cultivated cowpea and different alternative host plants especially in the family Leguminosae (Bottenberg et al., 1997; Arodokoun et al., 2006; Traoré et al., 2014).

2.4 Pod-sucking bugs (*Clavigralla tomentosicollis* and *Anoplocnemis curvipes*)

Pod-sucking bugs can cause a total loss of productivity to cowpea production, especially in Sudan zones where rainfall is between 600 and 1400 mm of water. After thrips, they are the second most damaging insect to cowpea pods during the seed-filling stage. In Africa, a complex of pod-sucking bugs predate cowpea pods and seeds, including *A. curvipes* and *C. tomentosicollis* (Singh and Allen, 1980; Singh and Jackai, 1985). In West Africa, *C. tomentosicollis* is the most widespread and damaging species of these. Females lay eggs on the underside of the leaves to avoid their exposure to sunlight and prevent washing off by rain splash. Hatched larvae undergo five instars before reaching adult stage. Both adults and larvae of *C. tomentosicollis* feed on all stages of the pods (including mature pods) by sucking the sap (Suh, 1986), causing premature pod drying and abnormal seed formation. The tolerable temperature range for a complete developmental cycle is 25°C–31°C (Dabiré, 2001). Like *C. tomentosicollis*, *A. curvipes* larvae undergo five nymphal instars. The adults are strong fliers and suck the sap from green pods, causing them to shrivel and dry prematurely with a resulting loss of seed (Singh and Allen, 1980).

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3 Applying molecular biology tools to cowpea insect pests

Next-generation sequencing (NGS) platforms have the capacity to produce previously unparalleled amounts of DNA sequence data and offer a rapid entry point into genomic research (Coates et al., 2011). Applications involving NGS data have been especially useful for genomic-level research on non-model organisms (McCombie et al., 1992; Ellegren, 2008; Sloan et al., 2012; Harismendy et al., 2009) and have facilitated hypothesis-driven research into a diversity of research questions (Harismendy et al., 2009; Rothberg and Leamon, 2008). NGS technologies use massively parallel pyrosequencing to collect millions of independent nucleotide sequence reads in very short time frames at a very low cost per nucleotide (Margulies et al., 2005; Moore et al., 2006; Wicker et al., 2006; Huse et al., 2007; Weber et al., 2007), such that researchers can acquire large amounts of DNA sequence data from organisms where no prior information had previously existed (Margam et al., 2011b,c; Agunbiade et al., 2013).

While this genomics revolution has ushered in a fundamental change in how agricultural crop pest control is investigated (Coates et al., 2015), and is evident within many recent research avenues aimed at understanding the cowpea pest complex. This has also occurred concurrently with a general trend in crop protection towards a reduction in chemical pesticide use due to heightened conscientiousness towards human health and environmental stewardship (Tedeschi, 2012). Thus, NGS data are sought to facilitate the development of novel genetics-based and species-specific methods of controlling insect pest populations that will improve the efficacy, while reducing adverse environmental impacts from current methods (Alphey and Bonsall, 2014).

In the case of most cowpea pests, a lack of sufficient population genetic data has hindered the estimation of gene flow across these insect populations within their endemic range, such that the regional scales necessary for effective insect resistance management (IRM) and IPM programmes remain difficult to assess. This scenario, however, is quickly changing with the merging and application of previous ecological data and NGS tools to the control of these insect pests (Poelchau et al., 2016). Cowpea researchers are currently developing molecular genetic markers from genomic sequence data that afford identification of not only genetic variation within and between populations of a cowpea pest species and their associated natural enemies but also geographic distributions and patterns of gene flow – hence, determining where the pest populations in the wet season originate and where the source population is endemic in the dry season. These data are critical for targeting and timing IPM-based control measures in the field, as well as enhancing biological control efforts by determining the coincidence of endogenous natural enemy populations. High-throughput single-nucleotide polymorphism (SNP) genotyping (Margam et al., 2011b), as well as microsatellite marker assays (Agunbiade et al., 2012 and 2014) developed from NGS data, was used to answer questions of temporal and spatial scale for *M. vitrata* migration, while the above-mentioned molecular marker work, combined with light-trapping data, helped to support the South–North migratory hypothesis: that insects observed in the north in the rainy season were most closely related to those found directly south in the endemic zone in the dry season. From these data, then, the most logical place to deploy a biocontrol agent would be in the endemic zones, with the long-term potential to minimize populations that may be migrating north.

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Findings by Margam et al. (2011a) further suggest that *M. vitrata* from West Africa (Old World) and Puerto Rico (New World) represent two distinct mitochondrial haplotype groups, and proposed that the samples are possibly a complex of sibling species. Studies that refine this prior haplotype divergence estimate and provide an estimated time of divergence between the New and Old World strains of *M. vitrata* are ongoing (Margam et al., 2011c; Agunbiade et al., 2016). Further characterization of *M. vitrata* populations collected from different host plants, especially in the more humid south of the West African country of Benin, suggests that host plants do not significantly influence the genetic structure of *M. vitrata* (Agunbiade et al., 2014). These prior studies demonstrate that genome-based NGS data can be applied to devise tools that increase our collective understanding of *M. vitrata* populations, some of which may be of practical applications for IPM and IRM; other components may be of only academic interest.

In the absence of whole-genome sequence assemblies, *de novo* transcriptome analysis has proven to be valuable for the identification of gene sequences, allelic variants and their expression levels in different developmental and metabolic pathways, for insecticide resistance traits and also to discover SNPs in model and non-model organisms (Sloan et al., 2012; Xue et al., 2010; Mittapalli et al., 2010; Poelchau et al., 2011). These polymorphisms can be developed into genetic markers for population genetic studies (Margam et al., 2011b). Much transcriptome research has been directed towards developing strategies to control the feeding of *M. vitrata* on cowpea crops, including understanding genetic mechanisms involved in insecticide resistance evolution and spread within insect populations, along with efforts to identify potential insecticidal RNA interference (RNAi) targets.

Recent shifts towards the use of more affordable and sustainable biocontrol measures have been initiated within West Africa (Adati et al., 2007; Amevoin et al., 2007). Some potential *M. vitrata* control strategies include the deployment of biopesticides (Oparaeke, 2010; Tamò et al., 2012) and the development of a transgenic cowpea that expresses *Bt* toxins (Cowpea CRSP, 2001). Transgenic cowpea that expresses a *Bt* Cry1Ab toxin is highly specific for lepidopteran insects such as *Maruca*. As such, these cowpea crops still remain susceptible to feeding damage and plant disease transmission by thrips, aphids and pod-sucking pests, including *A. craccivora*, *A. curvipes*, *C. tomentosicollis* and *M. sjostedti*.

The only method widely available to indigenous farmers in West Africa for controlling these non-lepidopteran pests is the application of chemical insecticides. Thus, the establishment of effective IRM plans for *A. craccivora*, *A. curvipes*, *C. tomentosicollis* and *M. sjostedti* may be critical for delaying the evolution of chemical insecticide resistance, as well as the possible evolution of *Bt* toxin resistance by *M. vitrata*. To partially address these concerns, Agunbiade et al. (2013) applied NGS technology to generate independent transcriptomes from normalized cDNA libraries in *A. curvipes*, *A. craccivora*, *C. tomentosicollis* and *M. sjostedti*. Annotation of individual gene transcripts identified candidate genes putatively involved in insecticide resistance, regulation of insect growth and response to disease transmission. The study was the first to report genomic data for these insect pests and provides an initial catalogue of molecular gene functions from several major field insect pests in cowpea cropping systems of West Africa. The future application of these genomics datasets might ultimately lead to a better understanding of the pest populations, with the long-term potential to improve the effectiveness of IPM programmes by defining pest–pathogen interactions and pest population dynamics that enhance the efficacy of biocontrol agents.

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4 Biological control approaches to sustainable IPM

IPM has been the strategy of choice for developing plant protection options in cowpea, relying on commonly implemented practices worldwide (Cook, 2000) and focusing on plant health in a holistic manner (Tamò et al., 2012). In an ideal world, the first line of defence against crop pests is host plant resistance. This approach has been explored extensively in the past with regard to cowpea insect pests (Singh et al., 1990; Jackai and Adalla, 1997). There have been promising sources of resistance/tolerance to aphids (Souleymane et al., 2013) and flower thrips (Abudulai et al., 2006), which are currently the focus of ongoing screening efforts. However, for some of the key pests such as the pod borer, *M. vitrata,* and pod-sucking bugs such as *C. tomentosicollis*, there is virtually no useful source of resistance in the cultivated germplasm. Nevertheless, some wild relatives of cowpea, for example, *Vigna vexillata,* do possess useful levels of resistance to these recalcitrant pests. Unfortunately, sustained efforts to cross these wild cowpea species with cultivated lines have remained largely unsuccessful (Fatokun, 2002).

As stated above, cowpea has also been transformed with a gene construct encoding a Cry1Ab endotoxin, targeting the legume pod borer. Not yet published laboratory assays and confined field trials from the African Agricultural Technology Foundation have confirmed the technical efficacy of this approach. A second-generation product expressing *Maruca* control toxins with two independent modes of action is currently under development as well. Both the first- and second-generation products will be used within the standard IPM stewardship framework to address IRM concerns. At the same time, work is underway to establish a more robust cowpea seed value chain in order to be able to distribute large amounts of *Bt* cowpea under the auspices of a robust stewardship model.

As a normal and accepted component of agricultural production, farmers very often apply chemical pesticides, if and where available and affordable. However, handling and utilizing chemical insecticides in the context of West African subsistence agriculture is challenging (Jackai and Adalla, 1997). Arguably, synthetic pesticides in the short term continue to provide good control for most of the pest problems, with the added advantage of their knock-down effect, which can be easily appreciated by the low-literate farmer (Singh et al., 1990). However, in the long term, synthetic pesticides need to be carefully evaluated for their possible adverse side effects which are starting to emerge even in rural areas of West Africa (e.g. Diabate et al., 2002). As described in Coulibaly and Lowenberg-DeBoer (2002), the first issues to be addressed while applying pesticides are those related to human health. In the developed world, pesticides are applied following strict regulations, including protective equipment and according to the instructions written on the accompanying documentation. In West Africa, in general, farmers perceive the use of protective equipment as an unnecessary burden because of the hot and humid climatic conditions. Moreover, resource-poor farmers very often do not consider the purchase of protective implements as a priority. This leads to the practice of spraying with no protective equipment at all. From an environmental perspective, the inappropriate application of pesticides can have serious long-term effects as well, including the evolution of insecticide resistance in target pests as is already documented for *M. vitrata* in Nigeria (Ekesi, 1999). Indiscriminate use of broad-spectrum insecticides, particularly at the beginning of the cropping season, very often results in elimination of natural enemies as well, which limits the control impact on pest populations later in the season, leading to pest outbreaks (Heong et al., 1992).

Over the last 10 years, alternative control methods relying on both biological control and biopesticides have been given serious consideration and have now reached the mainstream of cowpea plant protection (Tamò et al., 2003). Biological control has been

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considered for many years as having marginal importance in limiting cowpea pest populations (Singh et al., 1990) but has regained interest recently. Biological control easily integrates with other pest control options, such as host plant resistance, and is generally only negatively impacted by the inappropriate use of pesticides. Biological control, in fact, complements the limited levels of insect resistance, which have been put into improved varieties during years of hard work by the breeders.

Biological control involves putting agrobiodiversity to work, restoring disturbed ecosystem services or establishing new ones (Moonen and Barberi, 2008), whereby specific parasitoids and predators that target specific life history stages for optimal control are deployed. Hence, the first step in determining the potential for biological control of a pest in a given system starts with an assessment of its life history, including studies of trophic-level interactions with beneficial organisms (Hoelmer and Kirk, 2005). Our biodiversity assessment studies have revealed the presence of hitherto unexploited natural enemies for most of the cowpea pests, some of which are already in an advanced testing stage and are starting to see deployment.

An example involves the East/Central African strain of the hymenopteran thrips parasitoid, *Ceranisus femoratus*, which was released and became successfully established on nursery plots of the leguminous shrub, *Tephrosia candida*, in Benin, Southern Ghana and Southwestern Nigeria (Tamò et al., 2003). In Benin, we intensified our post-release assessment sampling to not only measure the area covered by the parasitoid but also to obtain quantitative data on its ecological impact in reducing the population of the target host. So far, we continue to observe significant differences in thrips larval abundance – up to a 43% reduction on two major host plants for *M. sjostedti*, *Pterocarpus santalinoides* and *Lonchocarpus sericeus* (Tamò et al., 2012). This substantial reduction has led to a limiting of damage to cowpea in the surrounding areas, for example, where these host plants can provide a reservoir of parasitoids during the off-season. If combined with improved host plant resistance in a good agronomic background and punctual applications of biopesticides, for example, the newly developed emulsifiable neem oil mixture (see Sokame et al., 2015), this will provide a solution for the thrips problem in cowpea by lowering the pest populations below EILs.

The other major pest, the pod borer *M. vitrata*, has also been the object of intensive studies focusing on locally available natural enemies in Africa (Taylor, 1967; Agyen-Sampong, 1978; Usua and Singh, 1978). However, Arodokoun et al. (2006) were the first to assess the presence and impact of hymenopteran parasitoids on widespread alternative host plants over a three-year period. From this work, it appeared that the locally available parasitoids were location-specific rather than host-specific and were therefore not able to control high levels of *M. vitrata* populations. Because the presumed area of origin of *M. vitrata* was suspected to be in the Tonkin area in South East Asia (Tamò et al., 2003), inter-regional collaborative studies were undertaken to scout for more adapted natural enemies, including hymenopteran parasitoids.

Consequently, biodiversity studies carried out in Taiwan revealed the presence of seven parasitoid species, all unknown from Africa (Huang et al., 2003). The first one to be tested in West Africa was *Apanteles taragamae* Viereck (Hymenoptera: Braconidae) due to its impressive field parasitism rates of up to 63% on *M. vitrata* feeding on *Sesbania cannabina* (Retz.) Pers. (Leguminosae: Fabaceae) leaves, a common green manure crop in tropical Asia. However, extensive studies on this parasitoids ecology and biology (Dannon et al., 2010a,b and 2012) revealed it as poorly adapted to West African conditions, particularly because it was not capable of recognizing major wild host plants for *M. vitrata* present in West Africa.

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Subsequent studies from Lao PDR, Taiwan and Vietnam indicated the presence of a larval parasitoid, *Therophilus javanus* (Bhat and Gupta, 1977), together with an egg-larval parasitoid, *Phanerotoma syleptae* Zettel (Hymenoptera: Braconidae), as important antagonists of *M. vitrata*. In fact, very recently, they have replaced *A. taragamae* as key parasitoids for *M. vitrata* in Taiwan (R. Srinivasan, AVRDC, pers. comm.). It is noteworthy to mention that these two organisms, albeit under a different nomenclature, had already been identified by Kalshoven (1950–1) as the possible cause for the low incidence of *M. vitrata* in Indonesia.

Both parasitoids have subsequently been introduced to the IITA laboratories in Benin, and, after clearance from the regulatory authorities, have been the object of experimental releases on patches of wild vegetation across Western Benin. So far, both organisms have been recovered from various host plants, with a clear preference of *P. syleptae* for legume trees and shrubs, and of *T. javanus* for herbaceous legumes including cultivated cowpea (B. Datinon, IITA, pers. comm.).

With a better grasp now of what needs to be considered for the development and deployment of a 'biocontrol pipeline' with regard to cowpea pests, rather than a reactive pest control approach using chemical pesticides as the main – and in many cases the sole – control option, we can propose a science-driven, proactive approach to IPM. Coupled with an educational component to elicit buy-in by farmers, we propose the term 'precision-IPM' to designate this approach. Given the future of pest control in light of climate change and changing societal domains, the need to involve information and communication technology (ICT) systems to understand and respond to pest patterns in real time, while remaining environmentally sustainable and economically viable, becomes mandatory.

In fact, one of the most challenging issues has been how to deploy IPM tactical knowledge to farmers with varying literacy levels, who typically live in rural areas, and generally speak a great diversity of non-national languages more fluently than the national language. To address this critical issue, a programme to format these knowledge strategies and concepts in an accessible form was needed, one that particularly allowed translation into local fluencies, while being appealing and electronically highly portable. The SAWBO video animations met all of these criteria.

5 Adoption of precision-IPM strategy by cowpea farmers

As primary stakeholders and implementers of agricultural technologies, it is important to study smallholder farmers and understand how they value alternative pest control strategies in their crop production decisions. This section discusses socio-economic research results from two separate farmer surveys conducted on cowpea producers in Benin and Burkina Faso. The discussion focuses on existing pest control characteristics and implications for sustainable agriculture, farmers' preferences for alternative pest control strategies, and other issues critical for adoption and scalability of the precision-IPM strategy across West Africa.

5.1 Existing pest control characteristics and farmers' awareness

In recent years, comprehensive farmer surveys have been carried out in two of the major cowpea-producing countries in West Africa, namely Benin (Agyekum et al., 2016a) and

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Table 1 Characteristics of smallholder cowpea production in Benin and Burkina Faso

Characteristics	Benin[1]	Burkina Faso[2]
Farmer/household		
Gender of person responsible for cowpea production decisions (% male)	69	99
Number of people living in household	7	10.5
Use of agricultural credit for cowpea production (% yes)	17	3
Household received remittances from relatives (% yes)	14	18
Income from non-crop sources (% yes)	59	89
Cowpea farms		
Land size for cowpea production (ha)	0.6	0.8
No. of cowpea fields grown per season	1	1.3
Was cowpea inter-cropped? (% yes)	9	37
Cowpea grain yield (kg/ha)	316	345
Portion of cowpea grains sold (%)	67	59
Did you harvest fodder? (% yes)	10	64
Existing pest management characteristics		
Application of chemical pesticides on cowpea crops (% yes)	88	79
Chemicals on other crops? (% yes)	14	3
How volume of pesticide use compares to previous years (% lower)	5	26
Satisfaction with effectiveness of pesticides (% yes)	65	70
No. of chemical applications per cowpea season	3	2.5
Chemical hazard awareness, and exposure to chemical pesticides		
Do you think pesticides are harmful to people? (% yes)	93	91
Knows colour label identifying most toxic pesticides (% yes)	11	18
Has anyone you know been sick due to pesticide poisoning? (% yes)	45	33
Hired labour for pesticide application? (% yes)	0	16
Does household use gloves during spraying? (% yes)	25	27
Use face mask to apply pesticides? (% yes)	24	27
Clothes/skin wet with pesticides after spraying? (% yes)	71	46
Reported chemical exposure symptoms, e.g. skin/eye issues (% yes)	57	52
Awareness of beneficial insects		
Farmer's awareness of beneficial insects (% yes)	9	8
Sample size (no. of households)	505	560

Sources: [1] Benin information is from Agyekum et al. (2016a).
[2] Information on Burkina Faso is from Reyes et al. (2013).

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Burkina Faso (Reyes et al., 2013). Each of the two field surveys interviewed over five hundred randomly selected farm households across several farming communities in the respective countries. Cowpea production data collected in the farmer surveys include pest pressure, pest control strategies, self-assessments of existing pest control methods, production costs, yield levels, prices, sources of household income, access to agricultural credit, household cash expenditure, assets owned by the household and socio-demographic characteristics. Table 1 is a cross-country comparison of both survey results. The surveys show that cowpea farmers in Benin and Burkina Faso have remarkable similarities, particularly on their current crop defence methods and awareness of associated risks to health.

On crop protection strategy, the majority of farmers apply chemical pesticides to control pest pressure on their cowpea fields. However, only a small fraction of farm households apply chemical pesticides on crops aside from cowpeas. Relative to other crops grown on farmers' fields, the widespread application of chemical pesticides on cowpeas is both a manifestation of the incessant pest attacks during cropping seasons and the importance of the crop to household food and income security. Furthermore, it is interesting to note that nearly all cowpea farmers believe chemical pesticides are harmful to human health. In spite of this level of awareness among smallholder farmers, survey results indicate limited use of personal protective equipment (PPE) such as gloves and protective masks; only a quarter of the farmers use some form of protection during chemical pesticide application.

The apparent lack of recommended PPE means that cowpea farmers may be at high risk of exposure to toxic active ingredients in chemical pesticides. Not surprisingly, more than half of the farmers reported cases of skin irritation and eye problems suffered after spraying chemical pesticides. Also, a quarter or more of the farm households reported knowing someone in their community who fell sick because of poisoning from chemical pesticide application on their farms.

The studies also assessed the farmers' awareness of environmental damage caused by misuse of chemical pesticides. Given the prevalence of broad-spectrum chemical pesticides in cowpea production across West Africa, farmers were asked if they were aware of any beneficial insects in their farming environment. More than 90% of farmers indicated an unawareness regarding potential disruptions to the ecosystem balance in the farming areas as a result of unintentionally killing natural enemies by an inappropriate use of broad-spectrum chemical pesticides.

5.2 Farmer pest control needs and adoption of precision-IPM strategy

To predict uptake of precision-IPM strategies, Agyekum et al. (2016b) implemented a choice experiment for cowpea farmers in Benin during the survey mentioned above (for details on choice experiments, see Kanninen, 2007; Bennett and Birol, 2010; Johnson et al., 2013). A conservative approach was employed in the choice experiment such that precision-IPM was deliberately presented as relatively worse in performance compared to a farmer's own chemical control method (in terms of cost, associated yield loss and labour input). Even with the relatively poor performance from the precision-IPM strategy, the majority of farmers indicated willingness to switch from their current chemical pest control method in favour of the innovative IPM method (see Fig. 4). The choice experiment results help reveal the trade-offs farmers are willing to make in their choice of pest management strategies.

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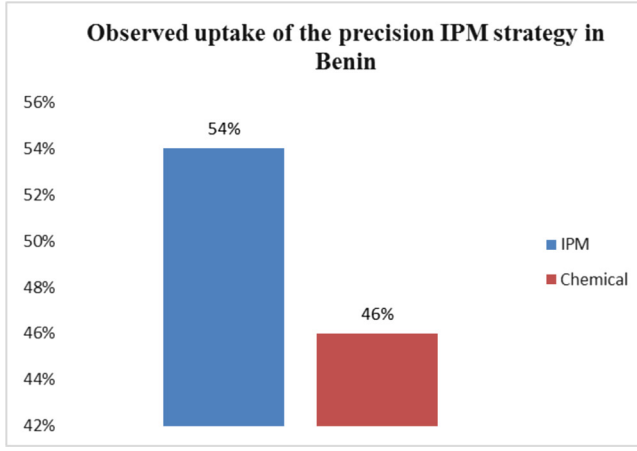


Figure 4 A choice experiment on preferences for alternative pest control methods conducted on more than five hundred cowpea farmers randomly selected across Benin. This chart shows the distribution of farmers' preferences when presented with the decision to choose between their own chemical pest control methods and the precision-IPM strategy. Note that the majority of farmers opted for the precision-IPM strategy even though the IPM scenarios presented in the experiment were intentionally described as costly (i.e. higher cost of biopesticides and more labour input) and less effective compared to existing chemical methods. Results show farmers desire to try alternative pest control methods that are safer for their health.

Agyekum et al. (2016b) show that cost, potential yield loss and labour requirements for the IPM strategy are important to farmers such that high values of these attributes would likely reduce uptake. Conversely, the socio-economic factors of age, gender, level of formal education and household income had no effect on potential adoption of the IPM method (Agyekum et al., 2016b). Farmer preference for the IPM strategy, then appears to be uniform, with a high potential for widespread adoption across West Africa.

Agyekum et al. (2016b) also explored the possible relationship between social pressure – in terms of the proportion of farmers in a community who choose to participate in an innovative IPM programme – and how this communal behaviour may impact other farmers' decision to adopt the precision-IPM strategy. Agyekum et al. (2016b) show a strong positive correlation between community participation rate and its influence on farmers' decision to choose the IPM method. Thus, farmers recognize that the success of the precision-IPM programme depends on cooperation from other community members in order to avoid the broad-spectrum chemical pesticides that would otherwise undermine the establishment of the biological control agents deployed in their farm environments.

6 SAWBO and mobile learning experiences

Founded in 2010 and publicly released in 2011, SAWBO's mission is to create educational animation materials presented in fluent local languages. To date, SAWBO has produced more than seventy videos in more than one hundred different languages. These videos

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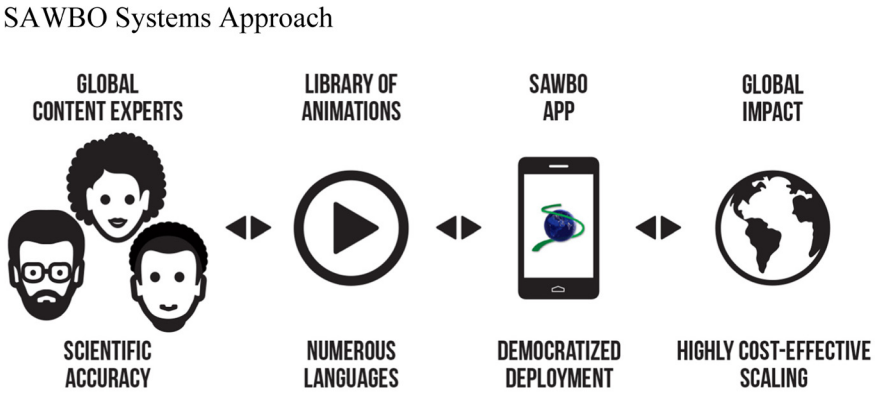


Figure 5 SAWBO systems approach.

span the agricultural, health and women's empowerment sectors and can be accessed from a variety of SAWBO channels for use on mobile phones, tablets, televisions, computers and overhead projectors. The programme relies on volunteers from all over the world to translate, record, voice overlay, share, deploy and train others. SAWBO values and has conducted research on indigenous knowledge (Bello-Bravo and Pittendrigh, 2012), aiming particularly to give voice to the most impoverished communities, to preserve their local knowledges and languages, and to share them globally.

The SAWBO systems approach entails the following: (1) to continually create educational content with experts on diverse topics, (2) to place content into diverse local languages and (3) to make it accessible to educators who can then (4) deploy such content in their communities as part of their own educational programmes. This approach allows organizations of any size – from small, community-based organizations to large government and international organizations – to access educational content in local languages that is scientifically accurate and accessible at no cost to these groups. This approach is illustrated in Fig. 5. Pre- and post-testing learning gain studies have shown that SAWBO animations are more popular and are also effective or more effective for increasing farmers' knowledge of IPM topics such as preparation of neem sprays as compared to traditional extension agent presentations of the same information (Bello-Bravo, unpublished results).

6.1 Information resources

As a next step in this ICT process, we are developing a prototype cell phone app to both draw upon data from the field and then deliver back pest control solutions to farmers in their own languages in a format that will be understandable by them across a great diversity of literacy levels. To ensure the effectiveness of educational content, a two-way communication mechanism, the Farmer Interface Application (FIA), is used to both deploy the educational material and then collect users' reaction to it while they are using it in the field. The FIA is a communication and notification portal that (1) enables farmers to have access to educational materials on proper pest scouting and management in cowpea,

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(2) guides farmers and records their observations in the field, (3) provides notification with proper action suggestions on the basis of the field collected data, (4) transmits the observations to a central database and an expert system (ES) along with time/date stamp and geo-location and (5) receives further notifications generated by the ES that warns farmers about the upcoming pest outbreaks.

FIA is a user-friendly application that allows farmers to reach the action point in three simple steps. The app is designed to convey information with simple graphics and easy-to-follow visual and auditory instructions. Once farmers learn about proper scouting techniques via a SAWBO animation, they are asked to go to the field and monitor a prescribed number of plants and record the level of infestation. The application then utilizes an internal algorithm to determine whether the farmers should conduct further scouting on a later date or should manage the pests now.

Relatedly, the ES itself is a cloud-based platform that collects information generated by FIA users and matches that information with other data sources to generate notifications using predictive models and algorithms. The system is designed to connect to weather and geographic information system (GIS)-based application programme interfaces (APIs) that provide updated information about climate variables, like temperature, moisture, rainfall and cloud cover as well as geographical variables such as elevation, rivers, mountains and so on. Updated periodically, this system can also take into consideration in-depth information about the genetic make-up of pest populations, on the basis of data input from researchers, and factor this into the models used for assessing insect pest threats. The ES provides a platform where experts can set certain thresholds for each variable to design predictive models that can generate and send specific notifications to FIA users on the basis of their geo-location. The ES platform is extremely flexible and scalable and can use multiple decision-making algorithms simultaneously.

7 Conclusion and future trends

Over the past decades, changes in the available pest control technologies used by crop producers have led to changes in IPM strategies. Conceptually, IPM strategies recognize that many environmental factors interact and work in conjunction to affect the abundance, distribution, movement and phenotype of insect pest populations. The systems approach of IPM leverages an in-depth knowledge of how management practices affect an insect's biology and other trophic interactions. It also involves the monitoring of pest populations to identify appropriate control measures as well as to aid in making decisions about how, when and where to apply them. Advances in genomics make it possible to better understand the dynamics of pest populations (e.g. movement patterns or biotypes that respond differently to host plant resistance traits), which may provide the requisite knowledge for developing new approaches for managing insects.

However, these more recent IPM strategies will have large-scale impact only if they can be coupled with effective educational and deployment tools that can be rapidly updated when new or other practical control approaches emerge. A mechanism will be needed to facilitate the flow of information between scientists and the end users who apply the strategies. In turn, scientists will need to rely on these kinds of real-time information sharing systems to obtain data on insect populations from local users, which can then be leveraged to continually and efficiently build and remodel solutions. Extension agents

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will also require a centralized system for information exchange so that they can access information about available practical pest control strategies.

This is facilitated by the advent of the Internet and cell phones, and increasingly so in Africa as cell phone availability and use continues to expand dramatically. These widely available technologies can be used not only to communicate information on pest populations between farmers and researchers but also to convey practical pest management recommendations back to farmers. The strategies developed in the preceding sections have already been applied within cowpea cropping systems in most West African countries, but such research and communication tactics can be applied to other cropping systems in other countries, both developing and developed.

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