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Challenges of Pest Management in the Twenty First Century: New Tools and Strategies to Combat Old and New Foes Alike

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The advent of synthetic chemical insecticides, introduced immediately following the Second World War, ushered in a new paradigm in crop protection and pest management. Chlorinated hydrocarbon, organophosphorous, and carbamate insecticides were inexpensive to produce, relatively straightforward to apply, fast-acting, and extremely cost effective. They also offered remarkable flexibility; for almost every pest, there were one or more chemical pesticides able to mitigate the problem. The benefits were readily measurable in economic terms, with every dollar spent on chemical pest management generating several dollars in increasing yield of produce (National Research Council, 2000).

But the comfort and complacency resulting from their widespread use began to be displaced some two decades following their introduction, with emerging observations of deleterious impacts on human health and to the environment. These hidden costs were difficult to enumerate in economic terms, exacerbating the challenge to the newly emerging regulatory agencies in industrialized countries that were tasked with weighing the obvious benefits of pesticide use against their difficult-to-measure risks.

To the credit of the agrochemical industry, they responded to concern over the deleterious effects—particularly human health impacts—by discovering newer insecticides with increasing selectivity toward targeted pests and decreasing toxicity to mammals (Perry et al., 1998). However, even the neonicotionoid class of insecticides, introduced in the 1990s and currently the most heavily used products of their kind worldwide, are now facing severe use restrictions owing to their negative effects on pollinators (Rundlof et al., 2015) and birds (Hallmann et al., 2014). And today, sophisticated computer-assisted molecular design is being used to produce the next generation of insecticides with greater efficacy, thus requiring lower rates of application to crops (Sparks et al., 2019).

Why all this effort? The simple answer is that after more than 70 years of research in the field of pest management, we are no closer to winning the "war against pests" than law enforcement agencies are to winning the "war on drugs." Worldwide, pre-harvest losses in major food crops average 30% (Oerke, 2006); compounding these losses are the complete loss of energy, water, and other resources (i.e., agricultural inputs) applied to that proportion of crops that are consumed by pests and diseases. On the other hand, it is widely accepted that in the absence of pesticides and host-plant resistance (including genetically-modified crops), those losses would reach levels of 50–80% in many instances (Oerke, 2006). So while the initial goal of pest management in agriculture was the *reduction in pre-harvest crop losses*, reasonably well-accomplished through the use of chemical insecticides, growing knowledge of the deleterious effects of widespread pesticide use spawned a secondary goal, namely the reduction in pre-harvest crop losses while *reducing chemical pesticide use*. This goal was at the core of the movement toward Integrated Pest Management (IPM),

TABLE 1 | Current and near-future pest management tools and tactics.

Category	Example
Exogenous crop protectants	Pesticides, including biopesticides Biocontrol agents Biostimulants
Endogenous crop protectants	Classical host-plant breeding for resistance Genetically-modified crops
Habitat manipulation/ecological engineering	Companion planting, "push-pull" systems Water management, cover crops, mulching
Protected cultivation	Glasshouse, poly tunnel, vertical farming
Pest population suppression	Pheromone-based mating disruption Sterile insect release programs Gene silencing (RNAi,etc.)

the use of two or more pest management tools aimed at minimizing pesticide use or using chemical pesticides as a "last resort."

At the same time that the agrochemical industry invested heavily in the creation of new and better insecticides, scientists in academia, government, and small private companies started developing a wide range of alternative tools and strategies to protect crops or otherwise mitigate pests, e.g., through population suppression techniques. Some of these alternative tools have enjoyed success, sometimes spectacularly so, albeit in limited application or contexts. The present-day exception to this is the widespread introduction of genetically-modified crops (maize, soybean, canola, cotton) that constitutively produce insecticidal proteins from *Bacillus thuringiensis* (Bt). These crops are extensively grown, especially in the Americas, and a recent meta-analysis on their impacts report average crop yield increases of 22% with reductions in chemical pesticide use of 37% (Klumper and Qaim, 2014).

Pest management tools and tactics can be divided into a number of broad categories (**Table 1**).

What can be said is that none of these alone have proven to be a panacea for pest management, and externally applied pesticides have remained the cornerstone of pest management in most food production systems because of their unparalleled breadth of applications. Furthermore, technological advances in formulation of pesticide active ingredients, whether conventional chemical insecticides or biopesticides, are likely to both improve their efficacy and reduce their adverse environmental effects substantially (De et al., 2014). Microencapsulation and nanoparticle formulation appear particularly promising in this regard (Bashir et al., 2016; Benelli, 2016).

Organic food production, which essentially eschews the use of synthetic pesticides, provides one interesting glimpse into the future of pest management. Limited 30 years ago to small-scale, local production near urban centers, it has been successfully adapted to an industrial scale, as demonstrated in California for example. Production of organic food in the USA and EU in the decade beginning in 2008 grew by 77%, but in 2017 that still only represented 5.5% of the total food supply in those jurisdictions (Marrone, 2019). In affluent countries, and those experiencing rapidly increasing standards of living, food safety concerns amongst the public are driving demand for organic food to the extent that demand exceeds supply. A key question is whether those bodies that provide certification for organic production, or the increasingly adopted standards for "sustainably" produced food, will come to embrace genetically modified (GM) food crops. Pickett (2016) makes a compelling case for the need for GM food crops, if we are to have any hope of producing the volumes of food needed by 2050 for the fast-growing human population. A major hurdle to the successful development and implementation of GM crops is public acceptability: public trust in pest management tools is low, and the government agencies tasked with regulating their use respond to public pressure. While scientists are in broad agreement that the risks from GM food production are extremely low, the perceived hazard remains high (Pickett et al., 2019). He further argues that this incongruity is a consequence of regulatory agencies focusing on the technology, rather than the safety of the products obtained using such technologies.

Another such technology is that of gene silencing through RNA interference (RNAi) (Gu and Knipple, 2013). This can be achieved through the exogenous application of double-stranded RNA (dsRNA) to a crop, as an insecticide, or endogenously through constitutive expression in a crop plant, so engineered. Being highly pest selective and with the potential for great efficacy, it share attributes and limitations with Bt toxin-expressing crops. One limitation of RNAi as a pest management tool is that pests must ingest a sufficient dose of the dsRNA to be killed and therefore delivery systems facilitating such acquisition need be developed. The first GM crop developed using this technology was maize engineered to manage the western corn rootworm (WCR; *Diabrotica virgifera virgifera*, Chrysomelidae); this cultivar, containing dsRNA as well as a toxic Bt protein, has been approved for food and feed in the USA and Canada (Fishilevich et al., 2016). However, the potential for resistance development in field populations of WCR has already been demonstrated (Khajuria et al., 2018), and field populations of WCR resistant to Bt-expressing maize have already been reported (Jakka et al., 2016). Thus far, coleopteran pests such as WCR and the Colorado potato beetle (*Leptinotarsa decemlineata*, Chrysomelidae) are the most susceptible to dsRNA, whereas major lepidopteran pests appear recalcitrant. This technology may yet prove a boon for management of phloem-feeding hemipterans that are not directly susceptible or not exposed to Bt toxins (Trapero et al., 2016), for example the brown planthopper (*Niliparvata lugens*, Delphacidae), the predominant pest of rice.

Yet another technology with great potential for pest management is CRISPR/Cas9-mediated genome editing (Taning et al., 2017). The possibility of engineering mosquito populations incapable of serving as vectors for human diseases such as yellow fever, dengue, or malaria is enticing, as would be subsequently engineered populations of hemipterous insects incapable of vectoring plant-pathogenic viruses. Suffice it to say, assessment of biosafety and environmental impacts of gene-edited insects, no matter the demonstrable benefits, will likely be burdensome.

Practitioners of organic production and IPM are both proponents of ecological intensification that promote ecosystem services such as pollination, biological control through natural enemies and nutrient cycling in agroecosystems. There are a number of management options both on-field (within a crop system) and off-field (in adjacent areas) that can have positive impacts on a wide range of ecosystem services (Bommarco et al., 2013). For example, an extensive international study demonstrated that planting nectar-producing plants (sesame) around rice fields reduced populations of two key pests (brown planthopper, *N. lugens* and the white backed planthopper, *Sogatella furcifera*) resulting in average yield increases of 5% while reducing insecticide applications by 70% (Gurr et al., 2016).

Outside of organic production, adoption of these practices has been somewhat hindered by a general lack of government support—both for research and direct support to farmers—and difficulties in scaling such practices in the context of the major field crops (viz., wheat, maize, soybean, and rice). However, a recent study of sugarcane production suggests that voluntary sustainability standards may make the implementation of such practices attainable (Smith et al., 2019).

Another major advance in pest management will be achieved by emerging technologies for automated early detection of pest populations and/or microclimatic conditions conducive to pest problems. Semi- and fully-autonomous devices and systems have recently been developed that are capable of detecting and locating pests in crops with speed, precision and accuracy unmatched by human scouts (Miresmailli et al., 2019; Partel et al., 2019). Harnessing machine learning, artificial intelligence and big data will only enhance the attributes of these systems, enabling decision-making by farmers in real time and with previously unimaginable geographic precision (Eli-Chukwu, 2019). Some of these devices are being developed to not only detect pests, but to deliver solutions (e.g., biocontrol agents, pheromones for mating disruption) precisely where and when needed within a crop. Systems such as these are already operational in both controlled environments (glasshouse vegetable production) and perennial orchards (tree fruits).

Exacerbating the longstanding challenges of pest management have been introductions of invasive species into new geographic regions. Massive increases in global trade and international travel in the past 50 years have allowed pests to reach new continents at rates not previously seen (Hulme, 2009). Just in this millennium we have seen intercontinental movement of key economic pests such as the tomato leafminer (*Tuta absoluta*, Gelichiidae), spotted wing drosophila (*Drosophila suzukii*, Drosophilidae), fall armyworm (*Spodoptera frugiperda*, Noctuidae), and brown marmorated stink bug (*Hyalomorpha halys,* Pentatomidae). Given the impracticality of monitoring all international cargo—how successful has this been in terms of stopping the movement of illicit drugs?—the introduction of new pests into new regions would appear to be inevitable. Given the potential economic impact of pests such as those noted above, their introduction into a new region can disrupt or even marginalize well-established pest management systems developed for indigenous pest species. In some countries, the risks have raised quarantine and advance monitoring tools on the list of government priorities.

Global climate change poses yet another challenge to sustainable crop production in the near future. Effects of increasing temperature on pest population dynamics had led to predictions of yield losses in the world's major grain crops—wheat, rice, and maize—of 10–25% per degree of global surface warming (Deutsch et al., 2018). Losses are estimated to be greatest in temperate zones producing the majority of the world's wheat and maize.

Altogether, there appear many emerging technologies and opportunities to achieve the goal of reducing pre-harvest crop losses. As I stated previously, none of these alone are likely to be a panacea for pest management except in very specific contexts. Production of GM crops has grown steadily over the past three decades, but even for those crops this technology has not entirely displaced the use of chemical pesticides. The extent to which we can lessen our dependence on pesticides in the foreseeable future—modifying the goal from reducing pre-harvest crop losses to achieving acceptable or optimal yields with fewer chemical inputs—will rely not only on advances in the science of pest management, but also on society's willingness to accept newer technologies along with their inherent, and presumably lesser, risks. As one expert explained, we may need a crisis in food production or prices to deviate from current pest management practices, as in the industrialized world, "the alternatives all come down to economics." Going forward, risk and regulation will be key determinants of pest management practice. We should hope, at the least, that government regulatory decisions are informed by good science in the future.

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The author confirms being the sole contributor of this work and has approved it for publication.

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