FORUM

Whatever Happened to IPM?

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Why are we even asking this question? Integrated pest management (IPM) is a term well known. It is used liberally by scientists and other practitioners without the need for definition. It is a major success story for society in the realms of agriculture, applied ecology, urban management, and public health (GAO 2001, Farrar et al. 2015). It has arguably penetrated the social consciousness more than any other applied ecological science, serves as a model for sustainable agriculture, and is consequently viewed as a rousing success (Kogan and Jepson 2007). But is this really true?

Although IPM is a widely recognized term, there are numerous IPM success stories, and people far and wide claim to practice it, we argue that it has lost its way. Many authors, including the authors of this paper, have discussed problems with the practice of IPM and the lack of adherence to its conceptual foundations (Pedigo et al. 1986, Pedigo and Higley 1992, Higley and Pedigo 1993, Higley and Pedigo 1996b, NRC 1996, Kogan 1998, Ratcliffe and Gray 2004, Gray et al. 2009, Higley and Peterson 2009, Neve et al. 2009, Menalled et al. 2016). So why are we belaboring this point now? First, there has been little formal discussion of IPM theory and its status over approximately the past 10 years. Second, the overwhelmingly successful adoption of prophylactic pest control tactics in the form of transgenic crops and seed treatments over the past 20 years has challenged the continuing development of IPM. This is especially true for major global food and fiber crops, for which scale and convenience are driving the adoption of prophylactic pest control as relatively inexpensive insurance. Third, the recent attention on using evolutionary biology in environmental and public health management should cause us to pause and revisit the foundations of IPM, but, more importantly, to also look deeply at its conceptual aspects and future development.

In this brief paper, which is meant to generate further discussion in our profession, we discuss the critical roles ecology and evolution play in IPM and then consider ways to reconnect them to, and thereby improve, IPM. Specifically, we recommend:

- Initiating new dialogue and research on the central tenets of IPM, especially evolution.
- Replacing *control* with *management*.
- Evolving from killing pests to managing host stress, where possible.
- Initiating host breeding programs specifically to breed for tolerance to pest injury.
- Emphasizing how to use tactics and de-emphasize the focus on tactics themselves.
- Recommitting to and updating Kogan's levels of IPM adoption.

Whatever Happened to Ecology and Evolution in Pest Management?

Ecology has been an important component of pest management since the inception of integrated control by Stern et al. (1959). The connection to ecology was further strengthened by the emergence of pest management (Geier 1966). The subsequent development of the concept and use of the term "integrated pest management" in the late 1960s and early 1970s solidified ecology's pivotal role in the paradigm. Kogan (1998) and Pedigo and Rice (2009) clearly presented the role of ecology in the history and current use of IPM.

The seminal paper by Stern et al. (1959) is replete with discussions of ecological relationships, especially as they pertain to population ecology. Early in the development of IPM, Smith (1962) stressed the importance of considering the total ecosystem, even calling it a first principle of IPM. Geier (1966) stated that pest management "was coined to emphasize the comprehensive nature of the approach, and to underline its preoccupation with ecological realities."

There are many definitions of IPM, many of which explicitly mention ecology. For example, Pedigo (1989) defined IPM as "a comprehensive approach to dealing with pests that strives to reduce pest status to tolerable levels by using methods that are effective, economically sound, and ecologically compatible." As it relates to sustainability, Higley and Wintersteen (1996) stated that pest management should address "(1) economic sustainability through minimizing the economic impact of pests, (2) ecological sustainability through employing management tactics so as to minimize selection pressure, and (3) environmental sustainability through minimizing the impact of management on the environment."

Ecology is clearly conceptually important to pest management. However, the successful use of ecological principles in the actual practice of pest management has been debated for many years. Some have argued that ecology is often overlooked in pest management, which even led to efforts to create a new paradigm, ecologically based pest management, in the late 1990s (NRC 1996, Kogan 1998).

There is little doubt that ecology forms a *theoretical* underpinning for pest management. In his famous maxim, Dobzhansky (1973) stated that nothing in biology makes sense, except in the light of evolution. Therefore, by extension—and without entertaining inevitable disagreements over definitions—ecology is included in Dobzhansky's statement.

Consequently, evolution holds a central place in pest management, yet its role in IPM has received relatively little attention. This is ironic because a chief impetus for the development of the integrated control concept by Stern et al. (1959) was the reality of arthropod resistance to insecticides. Indeed, they listed genetic plasticity of arthropods as the first of five serious problems leading to the need to develop integrated control. Early in the history of pest management, there was recognition of the importance of preventing the evolution of pest resistance to management tactics. However, this recognition was seemingly taken for granted and little, if any, extensive work on evolution and pest management has occurred. In his thorough review of the history of IPM, Kogan (1998) uses the word evolution only twice, and both uses are not in the context of biological evolution and pest management. Other than a general recognition of evolutionary issues within the context of pest resistance, evolution is rarely discussed as a key consideration in developing pest management programs. However, it must be discussed because we argue that the largest ecological and economic risk with contemporary pest management is the evolution of pest resistance to tactics.

We believe the consequences of not considering evolution in pest management are manifold. Even though the reality—indeed, inevitability—of the evolution of pest resistance to management tactics has been well known for decades, the focus remains on single control tactics themselves rather than on how tactics should be used. Pedigo and Higley (1996) labeled this current practice the "silver-bullet fetish" and defined it as "finding and using the most powerful tactics for killing pests." Similarly, Geier (1966) termed this "bulldozing nature." Although not discussing evolution per se, Pedigo and Higley (1996) stressed that, as opposed to an emphasis on individual tactics (which they called the "pest control strategy"), "IPM is a sustainable practice because it focuses on how tactics are used."

In recent years, there has been focus on the importance of applying evolutionary biology to address several seemingly intractable problems in biodiversity, public health, food security, and environmental health (Carroll et al. 2014). Managing pest resistance to tactics that impose strong selection pressures necessitates the need for applications of evolutionary biology, such as reducing phenotype–environment mismatches (i.e., when a population's phenotypic trait distribution differs from the environmental optimum) and incorporating combinatorial approaches to sustain management of pests (Carroll et al. 2014). We argue that IPM has a clear role to play here, provided that it is firmly connected to ecology and evolution.

Reconnecting Ecology and Evolution to IPM

If nothing in biology, ecology, and pest management makes sense except in the light of evolution, then how do we connect evolution to IPM beyond superficial discussions of the need to manage pest resistance to tactics such as pesticides? Nearly 60 years have passed since Stern et al. (1959), more than 50 years since Geier (1966), and more than 20 years since Higley and Pedigo (1996b), yet evolution continues to struggle to find solid footing in IPM. This is why the time has come to initiate new dialogue and research on IPM. In addition, if we are to more formally and more completely incorporate evolutionary considerations into IPM, the emphasis needs to shift broadly and resolutely from killing pests to managing host stress, where possible.

From Control to Management and From Killing Pests to Managing Host Stress

Fortunately, the shift from killing pests to managing host stress is occurring, at least in theory. Dealing with pests has progressed—albeit haphazardly and not comprehensively—along a spectrum from killing individual pest organisms to reducing pest status to reducing host injury to tolerable levels. Critical to this progression is the replacement of the concept of "control" with "management." Control implies a heavy-handed program focused on the pests themselves, resulting in the killing of pests and often a strong, concomitant selection for resistance. The focus on killing pests has been writ large in the past 20 years with the highly efficacious, prophylactic tactics of Bt crops and insecticide seed treatments. Because these are prophylactic tactics, there typically is little to no tolerance for any injury by the target pests (contrary to a key concept of IPM), although management of resistance to these tactics using refuges does allow for crop injury and pest survival.

Management implies a program focused on the "judicious use of means to accomplish a desired end" (Pedigo and Higley 1996), resulting in reducing pest status typically through modification of pest populations. However, management also includes reducing host injury to tolerable levels, which is a further refinement because it is not necessarily focused on modifying pest populations (Pedigo and Higley 1996, Pedigo and Rice 2009), and it therefore ameliorates selection for resistance.

Higley and Pedigo (1996a) stated, "Unless we reexamine the tenets of pest management and move away from control, we will continue to follow the path that has misled us in the past." Without question, evolution in the form of pest resistance to control tactics because of a focus on killing pests (what one of us, LGH, has called the "death paradigm" in several public and academic presentations) has led us down this path.

To not be misled further, we first need an updated definition of pest management. We define IPM here as a comprehensive approach to managing host stress that is economically and ecologically sustainable. This definition is similar to Pedigo's (1989), but additionally benefits from a focus on the concept of managing host stress as a way to incorporate evolution more formally in IPM. In our context, a host is the receptor of a pest's activity or injury, so it can include plants or animals, including humans.

We argue that managing host stress is a further desirable refinement yet to be realized. By focusing attention on managing host stress, rather than on reducing pest status or host injury, evolution can more fully infiltrate IPM. For example, eco-evolutionary dynamics can be incorporated more easily when the emphasis is on a crop host rather than its pest, taking into account the stresses it experiences, the cropping system, and the agroecosystem (Nicholls and Altieri 2007, Carroll et al. 2014).

Pest scientists understandably focus on pest biology and ecology, but a further improvement in incorporating evolution in pest management is an emphasis on host–pest relationships (Higley and Peterson 1996, Peterson 1996, Peterson and Higley 2001). Selection pressure, including reciprocal selection, can be better understood when these often complex host–pest relationships are placed within the context of ecosystem dynamics (Neve et al. 2009, Carroll et al. 2014).

Obviously, there are practical and ethical limitations to shifting to a total focus on managing host stress. In some cases, killing pests is our only option because we cannot tolerate any (or practically any) injury to hosts. This is most notable with medical pests and pests that cause aesthetic and quality losses. In the longstanding case of lack of consumer tolerance to cosmetic injury to food, we must make progress, but how?

Tolerance: The Forgotten Child of Host Resistance

We need to systematically incorporate tolerance of pest injury into pest management programs. Pedigo and Higley (1992) stated, "Plants that can tolerate or compensate for injury do not place selection pressures on pest populations. Therefore, the benefits of tolerance and compensation in plants are sustainable and permanent, making their use the consummate IPM tactic." The role of tolerance in IPM is unarguably clear. Tolerance, whether as a type of resistance or as an important concept of economic injury levels, ameliorates selection for pest resistance to tactics (Pedigo and Rice 2009, Peterson et al. 2017).

> "We define IPM here as a comprehensive approach to managing host stress that is economically and ecologically sustainable."

To that end, we need to encourage and fund research and breeding programs in both the public and private sectors specifically for making hosts more tolerant to pest injury. This is, of course, much easier said than done. It is exceedingly difficult to make plants tolerant to pests when they cause direct injury, i.e., injury to yield-forming or marketable organs (Peterson and Higley 2001). It is easier to make plants tolerant to indirect injury, i.e., injury to non-yield-forming organs, but even this is very difficult (Peterson et al. 2017).

There are several constraints to developing tolerant crops and other hosts. These include identifying tolerance, characterizing tolerance mechanisms, and understanding the genetics underlying tolerance (Velusamy and Heinrichs 1986, Delaney and Macedo 2001, Peterson et al. 2017). In addition, tolerance mechanisms are dependent on plant biochemical, physiological, and morphological responses, not insect responses. These responses are very complex and likely involve source–sink interactions and carbon–nitrogen dynamics that are, in turn, poorly understood (Rosenthal and Kotanen 1994). A more pest-tolerant plant may be agronomically less desirable or commercially less marketable. Also, producers have to accept that pest injury to their crop does not necessarily mean economic loss is occurring. Indeed, one could ask, "Can agricultural producers tolerate tolerance?"

However, there are now precision-breeding techniques such as marker-assisted selection and gene editing that may be able to attain greater levels of tolerance while at the same time providing high-quality, high-yielding crops. These breeding techniques should be rigorously explored because of the benefits of host tolerance in IPM systems (Peterson et al. 2017). Despite the promise of incorporating host tolerance in IPM, though, there will always be a role for the use of curative tactics for unexpected and occasional pests, and for those that cannot be managed otherwise.

Tactics vs. How to Use Tactics

In addition to a focus on host stress, we need to continue to move more pointedly from an emphasis on tactics to an emphasis on how to use tactics. The use of tactics has direct implications for selection pressure and therefore for sustainable pest management. By focusing on *how* to use tactics, we can ensure that we are incorporating evolutionary considerations into IPM. This focus has been largely overshadowed by the discovery and use of tactics without much regard for how to use them. We refer to this as the "have-technology-will-use syndrome" and it is, of course, another aspect of the "silver-bullet fetish." We argue for a determined focus on how to use tactics. For example, current approaches to resistance management for antibiotic drug use in public health, as well as for Bt crops in agriculture, may have relevance (Carroll et al. 2014).

The topics of sampling and economic thresholds are closely allied to the focus on management, host stress, and the proper use of tactics. Elsewhere, we have discussed in depth the importance of sampling and economic thresholds to IPM (Pedigo 1993, Peterson 1996), but we stress here that renewed emphasis should be placed on alleviating the time-intensive labor of sampling by using new approaches such as electronic sensors and big data analysis to quantify pests and/or injury. We also should have a renewed emphasis on the development of economic thresholds. Currently, there are relatively few *calculated* economic injury levels and economic thresholds (as opposed to nominal thresholds) for pest species (Peterson 1996, Leather and Atanasova 2017,

Table 1. Attributes of the three levels of IPM integration as modified from Kogan (1998).

Attributes	IPM Level I	IPM Level II	IPM Level III
Agricultural scales	• Host, field	• Host/crop community	• Agroecosystem, regional production system
Socioeconomic scales	• Individual, household	• Farm, neighborhood	• Village, co-op, county/province
Ecological scales	• Individual, population	• Community	• Ecosystem, landscape, biosphere
Focus of IPM level	• Management strategies for single species or species complexes	• Multiple pest interactions and management strategies	• Management of pests and host stress within and across production systems
IPM strategies	• Pest sampling • Economic thresholds • Preventive and curative management tactics • Tolerance of pest injury • Emphasis on how to use tactics • Evolutionary considerations	• Habitat management • Host–pest models	• Ecosystem- and landscape-level processes and models

Ramsden et al. 2017), but an increase in the number of pest species with economic thresholds (and a concomitant improvement in the efficiency of sampling) will help sustain IPM into the future.

Recommitment to and Update of Kogan's Levels of IPM Integration

Kogan (1998) argued for three levels of IPM implementation as a way to encourage progression along increasing ecological, socioeconomic, and agricultural scales and complexity. Level I involves control strategies for single species or species complexes. Strategies may include field scouting for pests and natural enemies, use of economic thresholds, use of cultural controls, and selective use of pesticides. Level II involves multiple-pest interactions and their control tactics. In addition to Level I strategies, Level II strategies may include habitat management, expert systems, dynamic host/pest models, and community-level considerations. Level III involves multiple pests and their controls within multiple-cropping systems. In addition to Level I and II strategies, strategies may also include ecosystem-level processes (Kogan 1988, Kogan 1998).

We recommend that Kogan's (1988) scheme be used to reinvigorate IPM. As such, we have revised the scheme to incorporate our five recommendations (Table 1). In particular, we have substituted "management" for "control"; added additional agricultural, socioeconomic, and ecological scales; added or revised some foci of IPM levels; and added or revised strategies for some IPM levels. Of special note is that we have included "tolerance of pest injury," "emphasis on how to use tactics," and "evolutionary considerations" within the IPM Strategies for IPM Level I. This was done to emphasize the importance of these strategies even at the first level of IPM integration.

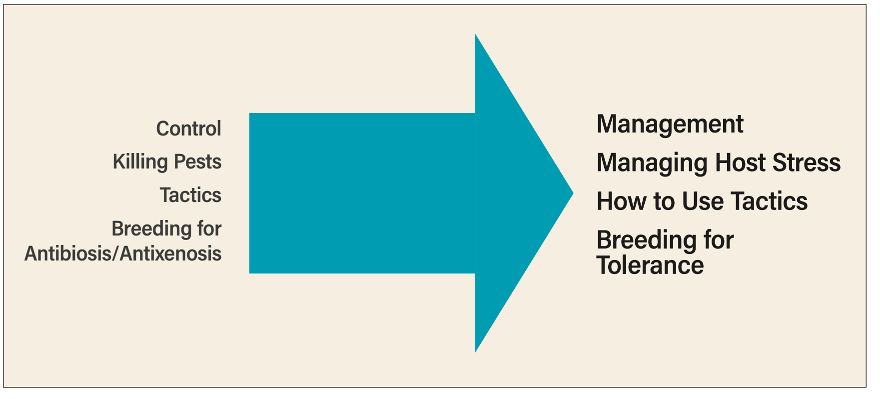

Figure 1. The needed evolution of IPM tactics. The current emphasis is on the left; the needed emphasis is on the right.

Conclusions

Our six recommendations should be supported by adequate funding to ensure that progress is made. For example, the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA NIFA) Agriculture and Food Research Initiative (AFRI) Foundational Program and other programs could include priority areas for competitive grant funding that addresses crop breeding for tolerance to insect, weed, or pathogen injury. Another area of grant funding and research and development investment by the private sector (presented here as an example) could include using sensors and big data to automate real-time quantification of pests and pest injury. Overcoming the sampling bottleneck to IPM implementation could lead directly to enhanced curative management of pests by developing economic thresholds for many more species than currently exist (Peterson 1996, Leather and Atanasova 2017).

Beyond research funding, there are broader and more important issues that must be considered and acted on. We must figure out how to "move the needle" with respect to perceptions by agricultural producers and consumers about tolerance of non-economic injury. We must fully engage economists and incorporate contemporary economics, particularly environmental economics, to ensure that our suggested actions can be economically justified and therefore adopted.

Our suggestions require a commitment to thinking about—and acting on—pests as part of the management of a system, with the host being central to that system (Fig. 1). This is in stark contrast to the more common approach of focusing on the pest as the entity to be controlled. Although it comes with numerous additional challenges, we should be adaptively managing agroecosystems, urban ecosystems, and natural ecosystems, not attempting to control one or a few organisms within these systems.

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