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Sampling plans, selective insecticides and sustainability: the case for IPM as 'informed pest management'

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Abstract

Integrated Pest Management (IPM) is considered the central paradigm of insect pest management and is often characterized as a comprehensive use of multiple control tactics to reduce pest status while minimizing economic and environmental costs. As the principal precursor of IPM, the integrated control concept formulated the economic theory behind pest management decisions and specified an applied methodology for carrying out pest control. Sampling, economic thresholds and selective insecticides were three of the critical elements of that methodology and are now considered indispensable to the goals of IPM. We examine each of these elements in the context of contemporaneous information as well as accumulated experience and knowledge required for their skillful implementation in an IPM program. We conclude that while IPM is principally about integrating control tactics into an effective and sustainable approach to pest control, this overarching goal can only be achieved through well-trained practitioners, knowledgeable of the tenets conceived in the integrated control concept that ultimately yield informed pest management.

Keywords: Integrated Pest Management; IPM; biocontrol; resistance; selective insecticides; sampling protocol

1 INTRODUCTION

Integrated Pest Management in its most literal form has been practiced ever since humankind began to cultivate plants for food and fiber. Once the concept was born that particular plants could be nurtured and relied upon as sources of food and fiber, caring for them would likely have involved learning to recognize destructive pests and implementing whatever mechanical and cultural means were available to prevent losses. At different points during the evolution of agriculture, various botanical extracts and oils were incorporated along with inorganic minerals such as sulfur and arsenic into rudimentary forms of chemical control.[1] Even selective propagation of seeds from plants that tolerated pest attack was likely part of an unconscious, or perhaps a reasoned, strategy to protect crops from competitors. While the historical integration of multiple control tactics was vital to bringing civilizations through 10 000 years of agricultural development, at no known time did it rise to the organized, formal structure of pest control that is recognized today as IPM.

The inception and growth of IPM as a discipline within the agricultural sciences is a relatively recent phenomenon that traces back to the advent of synthetic organic pesticides and the enormous impact they began to exert on agriculture during the late 1940s and 1950s. Although numerous expressions of concern about over-reliance on pesticides and the negative repercussions they were having on the agro-ecosystem also began at this time,[2] there was no development of an alternative strategy to mitigate intensive pesticide use until Stern *et al*.[3] synthesized and published the integrated control concept. As pointed out by Kogan,[4] the term 'integrated control' had been used previously by authors who were gaining awareness of the disruptive influences of pesticides with respect to pest resurgences,[5–7] secondary outbreaks[8,9] and the increasing incidence of insecticide resistance.[10–12] But without a formalized strategy available for addressing excessive pesticide use, and no alternative plan that could enable biological control to exert its full potential while retaining the capacity to treat with pesticides when needed, there were few prospects that the theory-less term 'integrated control' could alone provide an alternative approach to intensive chemical control, or develop into a new pest management movement.

This was not the case for the integrated control concept of Stern *et al*.[3] which immediately ignited great interest among concerned field entomologists as a rational framework for mitigating problems associated with increasing dependency on pesticides. Significantly, it was published 3 years before Rachel Carson's book *Silent Spring*,[13] a tribute to Stern and his colleagues[3] for their early awareness of the ecological hazards of rampant pesticide use. Even more impressively, the integrated control concept at once provided a theoretical basis and applied methodology for a more holistic approach to pest management. One of the remarkable aspects was its completeness in terms of providing theoretical underpinnings for the control decisions required of pest managers, but also for its practical understanding of how ecosystem complexity influenced pest populations and, in turn, the management responses necessary to bring about integration of biological and chemical control. The economic injury level (EIL),

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and the associated economic threshold (ET), took into account intrinsic differences among pest species as well as differences among 'crop, season, area, and desire of man'[3] that affected pest populations and the control actions taken against them. Because of their universality, ET and EIL enabled a pest management decision-making framework to be established for virtually any crop and arthropod pest. These bio-economic constructs provided the guidelines, along with other management approaches detailed in the integrated control concept, for carrying out the following recommendation offered subsequently in *Silent Spring*:[13]

> Practical advice should be 'Spray as little as you possibly can' rather than 'Spray to the limit of your capacity'... Pressure on the pest population should always be as slight as possible.

If there is one phrase that best sums up the underlying goal of IPM, it is 'Spray as little as you possibly can'. Without the advent of synthetic organic pesticides and the ensuing escalation in the use of chemical control, it is doubtful that the integrated control concept would have been conceived, or that IPM would have developed into the central discipline for pest management that it now represents. The application of toxic chemicals to protect crops from destructive pests remains pre-eminent in applied pest control even though society's approval remains hesitant at best. Declining public support for pesticides and increasing regulatory restrictions are placing greater pressure on growers and pest managers to turn out the same high quality produce and other food crops that consumers have come to expect, but with fewer of the reliable old compounds that have served as cornerstones of many IPM programs.

At a time when recent shortages and suspended exports of domestic food stockpiles[14] remind us of the vulnerability inherent in a world population pushing towards seven billion, the importance of IPM as a proficient and scientifically grounded discipline becomes ever more critical. Changing social attitudes, a burgeoning human population and evolving pest problems are all potentially conspiring to place IPM at a crossroads. In the 50 years since publication of the integrated control concept, tremendous growth in biological knowledge and development of technological tools for managing pest populations have occurred.

The amazing foresight of Stern and colleagues[3] concerning the importance of population sampling and prediction, augmentation of natural enemies, and the use of selective insecticides for minimizing impact on existing natural enemies in the system has become more of a reality and more implementable than ever before. Sampling theory for arthropods has grown to be a mature science, order-on-demand natural enemies can now be shipped anywhere in the world, and a profusion of new, selective modes of action in insecticides are proving highly effective against target populations without decimating beneficial arthropods. The opportunities are unparalleled for incorporating all of these approaches into refined IPM programs that reduce pesticide inputs. The challenge, however, is to use them in a knowledgeable and well-coordinated manner that in effect elevates the term 'integrated' to a higher meaning as it should be used in IPM. Without the fundamental knowledge about the pest and host crop, or the real-time information required to make informed and rational decisions, the meaning of 'integrated' reverts to its most literal form described in the opening paragraph – merely an ad hoc collection of multiple control tactics.

The acceptance and widespread recognition of IPM as the central paradigm of pest management has been a positive development in terms of its implied goal to reduce pesticide use through knowledgeable and coordinated use of alternative practices. Ironically, its very familiarity may be counter-productive in terms of the level of rigor by which it is practiced. There are too many instances in which the acronym IPM is used to describe pest control of any form no matter how far the departure from IPM principles. The often loose association between IPM and all known forms of pest control prompted one author to comment about 'the other IPM' – integrated pesticide management[15] and led to another cynical suggestion that the practical meaning of the 'I' in IPM might sometimes be more appropriately defined as 'incidental to pest management'.[16] Still others have expressed concern over the limited implementation of IPM altogether[17] or about various conflicts that confront growers and preclude wider adoption of IPM[18] as a standard approach to pest control.

Our goal with this paper will be to emphasize IPM as a knowledge-driven discipline that is dependent on both academic and field-based information to effectively integrate pest control strategies. We will consider how three of the more critical elements of an informed IPM program – sampling, thresholds and selective insecticides – are indispensable to attaining the goals of IPM through regularly updated information on infestation densities, but also to making the right decision in terms of treating or not treating, and choosing the most appropriate materials when treatment is necessary. These important elements of IPM also will be considered within the context of a sustainable IPM that is more plausible through informed rather than haphazard pest management.

2 THRESHOLDS AND SAMPLING PLANS – INTEGRAL TO IPM

Nowhere is the need for information more critical than in the two key elements that have come to define IPM over the past five decades, thresholds to inform when intervention is necessary and sampling to provide real-time information on pest abundance. Stern and colleagues[3] are widely credited with developing and introducing the concept of the EIL and the associated ET. These authors simply defined the EIL as 'the lowest population density that will cause economic damage' whereas the ET is simply 'the density at which control measure should be determined to prevent an increasing pest populations from reaching the economic injury level'. Subsequent workers elaborated more specific and mathematically based definitions that pushed the concepts forward (see references 19 and 20 for reviews). Regardless, these austere, but sophisticated concepts put forth by Stern *et al.*[3] formed the foundation and central organizing principles of all pest management activities that ensued from the 1960s onward.

Mathematically, the EIL represents the magnitude of pest equivalents of injury to the commodity of interest when the pest induced loss equals the cost of the control tactic implemented. It can be generally given as $EIL = C/VDK$, where C is the cost of control ($\$ \text{ ha}^{-1}$), V is the market value of the product (say, $\$ \text{ kg}^{-1}$), D is loss in yield from one pest equivalent (kg ha^{-1}), and K is the proportional reduction in the pest due to the control tactic.[20,21] As is evident from this relationship, the EIL is dynamic because the factors that comprise it are themselves subject to change. Commodity values and control costs are variable over time and region, and the relationship between pest damage and yield loss may also vary over time and space depending on factors such as plant or animal growth stage, cultivar or breed, and other factors.[22–32] The economic threshold is the operational pest density triggering control action and may depend on a broad array of factors, including population growth trajectories and how natural forces, for example natural enemies, may alter these trajectories.[33–37]

Knowledge and understanding of the multiple factors affecting both EILs and ETs are central to their effective and efficient implementation as part of an IPM program.

Pedigo *et al.*[20] point out that research to develop EILs and ETs for specific pests and systems lagged the introduction of the concepts of Stern *et al.*[3] by over a decade. Using articles dealing with EILs and ETs published in the *Journal of Economic Entomology* as a proxy for activity worldwide, there have been over 105 original research studies on these topics from 1970 to early 2009 with the majority published during the 1980s, and a relative decline in activity over the past two decades. A wide range of commodities have been studied, including field crops (corn, cotton, sorghum, wheat, soybean, sugar beet, tobacco, peanut, sunflower, rice), fruits and vegetables (bean, cantaloupe, potato, pepper, tomato, cabbage, onion, carrot, cauliflower, asparagus, pea, apple, strawberry), forage alfalfa, turf, rangelands, ornamentals (impatiens, azalea, pin oak, peppermint), cattle and poultry. About half of these studies determined EILs while the remainder reported on either economic or action thresholds, some of which might more properly be classed as EILs. It is worth noting that scientific studies are not the only source of information on thresholds. Quite frequently, so-called nominal thresholds, derived from experience and trial and error of extension personnel and/or consultants and producers, is the norm and often serve as an important place holder while more robust intervention levels are developed.

Sampling is a fundamental requisite to implementing any type of prescriptive control through adherence to thresholds and also to developing basic foundational knowledge of pest dynamics, and eventually EILs and ETs. Stern *et al.*[3] emphasized the important role of sampling in integrated control and further stressed the critical need for rapid and simple sampling methods that would be adopted and readily employed by consultants and/or producers. A wealth of theory and practice on sampling has amassed since the introduction of the integrated control concept[38–42] that has, in part, helped to make the techniques and methods for developing sampling protocols more accessible to a broader, but still a somewhat limited number of scientists. Approaches can range from relatively simple random sampling models for estimating mean densities with a prescribed precision to more sophisticated sequential models based on complete count or presence–absence (binomial) data that accurately classify population density as above or below a critical or threshold level within prescribed boundaries.

Sampling plans, which specify the general protocols for how samples should be collected and how many samples units should be taken, are based on research to understand the spatial distribution and variability of pest populations in the commodity of interest. Although fixed-precision sampling plans, based on either fixed sample size or sequential protocols, are more common for estimating pest density during developmental phases of an IPM program, they are generally less accurate and less efficient than plans based on classification of pest density relative to a threshold level, especially if a sequential approach is used to determine sample size. With sequential classification sampling a relatively small sample size is needed when pest populations are well below or well above the threshold, leading to savings of time and effort by the scout when populations are of no concern or of great concern, respectively. On the other hand, sample sizes can be quite large when the population is near the threshold so that pest density can be more accurately classified. The self-adjusting nature of a sequential plan leads to more accurate decision making but it also imposes some constraints to implementation and adoption that often lead to the eventual deployment of a fixed sample size protocol.[43] For example, Naranjo *et al.*[44,45] developed and validated an efficient binomial sequential sampling plan for classifying density of *Bemisia tabaci* (Gennadius) in the cotton system, but the plan was eventually delivered to consultants and producers as a fixed sample size classification scheme.[46]

Again, examining the sampling literature as applied to IPM in the *Journal of Economic Entomology* as a proxy to worldwide activity, we find the complete range of sampling methods and plans in multiple commodities.[47–56] From 1970 through early 2009 a total of nearly 60 studies were published in this journal that had relevance to implementing economic or action thresholds through definition of a sampling method or plan. Although it is somewhat problematic to draw too strong an inference from the articles in a single journal, this ratio of sampling plans to EILs and ETs would suggest that roughly half of the thresholds that have been developed have not been accompanied by a corresponding sampling plan for their effective implementation.

One additional issue with regard to sample plans is validation. Ideally, sampling plans should be developed from robust data encompassing the range of environmental conditions likely to be encountered. In practice, they are often developed from a restricted range of observations but used under a novel array of environmental conditions. Thus, validation of a sampling plan is an integral component in the process and may be particularly important for sampling plans developed for applying a decision rule (ET). An incorrect decision precipitated by a non-validated sampling plan may have important economic, as well as environmental consequences. Various tools for validating sampling plans have been available since the early 1990s.[40,42,57] Of the roughly 60 IPM-related sample plans noted above, only 11 employed some sort of validation procedure to test the sampling plan.

The delivery and implementation of decision protocols based on developed thresholds and sound sampling plans often fall within the purview of the extension service, which is the main artery for information delivery to pest control advisors and producers at the local level. As later emphasized by two of the authors of the integrated control concept '... implementation programs cannot move far ahead without parallel educational programs'.[58] Overall, the degree to which EILs and associated ET action or nominal thresholds have been delivered, implemented and adopted by producers is difficult to accurately judge as these activities often go unheralded and unpublished. High levels of scouting are done in certain crops. For example, about 50% of USA cotton hectarage was scouted an average of 1.3 times per week across the cotton belt in 2006 and the scouting rate was >90% in states such as Arizona, Louisiana, and South Carolina.[59] Whether these scouts and the producers employing them follow the decision protocols is again difficult to gauge. Smith and Huffaker[58] further state

> To improve implementation of integrated control programs, an immediate broad educational approach must be made, including training and retraining of crop protection and pest management specialists and the education of farmers.

An example of this process is provided in another article in this special issue.[60]

3 SELECTIVE INSECTICIDES

Another of the key approaches emphasized in the integrated control concept was the development and use of selective insecticides to foster biological control. Stern *et al*.[3] differentiated between insecticides that were selective in their toxicity and those that were not, but noted that the latter group could nonetheless be used in a way to maximize ecological selectivity[6] and reduce non-target effects. They suggested that selective applications could be achieved by lowering the dose rate to a level sufficient to control the pest population, by targeting only those areas where a pest/parasitoid ratio is unfavorable, and by timing an application to produce relatively greater mortality on the pest population using intimate knowledge of the diurnal behavior patterns of pest and natural enemies. Although a dependency on knowledge was specified only for the third tactic, in reality the first two tactics also require thorough knowledge with respect to defining an effective insecticide dose against the target population, or in identifying a field or section of a field where the pest population has increased relative to parasitoids or predators. By using ecological knowledge and current information on pest status attained through sampling, insecticide treatments can conceivably be restrained to enable a more finessed approach to pest management.

Much of our concept regarding insecticide selectivity is biased towards what Ripper and co-workers[6,61] termed 'physiological selectivity'. In a broader sense, this is a relative measure also used to differentiate the toxicity of a compound among different classes of animals including mammals, birds, fish, reptiles, amphibians, and arthropods. Insecticide selectivity is a critically important concept at this wider scope for its contribution to evaluating the safety and health risks imposed by a compound when non-target exposure occurs. Higher selectivity towards arthropods is a desirable quality, indicating that relative toxicity is greater for arthropods and lesser towards other invertebrates and vertebrates.[62] Non-target organisms including humans are vulnerable to pesticide aerosols in the atmosphere, residues on food plants and in the soil, as well as dissolved in water throughout the ecosphere. There has been strong social and governmental pressure against toxic pesticides that contribute to environmental degradation and are injurious to human health. For example, the Food Quality Protection Act in the United States was enacted into law in 1996 to establish new safety standards for pesticide residues in food and increase protection of infants and children.[63] Prior to that, the US Environmental Protection Agency enacted the Reduced-Risk Pesticides Initiative in 1993 to encourage development of pesticides that present lower risks to public health and the environment.[64] Whereas this initiative provides guidance on the safety of pesticides to humans and the environment, it does not delve into information on the relative selectivity of reduced-risk products to various insect taxa.

With greater activism against toxic pesticides entering the environment, agrochemical companies have responded by developing new insecticides that are generally much more selective towards arthropods than was the case when the integrated control concept was introduced.[3] Many of these are being adopted with increasing frequency, although organophosphates alone still accounted for 24.7% of market share of global insecticide sales in 2004, followed by pyrethroids at 19.5% and carbamates at 10.5%.[65] There are very few signs of insecticide selectivity in any of these three classes, with all of them generally being described as having broad-spectrum toxicity profiles within phylum Arthropoda as well as kingdom Animalia, the lone exception being the pyrethroids that are generally less toxic to mammals.[66]

Despite the persistence in agriculture of relatively non-selective organophosphates, carbamates and pyrethroids, newer insecticides with improved selectivity are slowly gaining market share,[67] hopefully in part due to more strategic thinking among an increasing number of IPM practitioners carrying out the principles of the integrated control concept. One of the most encouraging signs regarding market shifts has been the decline in market share of organophosphate and carbamate compounds that target acetylcholinesterase (AChE) in synaptic junctions of the central nervous system. Combined market share of these AChE inhibitors was 71% in 1987 but by 1999 had declined to 52%.[68] Much of this decline is attributable to the rise of neonicotinoid insecticides beginning with the introduction of imidacloprid. There are now a total of seven neonicotinoids that had been commercialized and represented 15.7% of market share of global insecticide sales in 2004. The neonicotinoids have the positive attribute of being relatively selective among animal phyla with overall low acute toxicities to mammals, birds and fish.[69] They also show selectivity among different insect orders, but vary in their selectivity by compound and by application. For example, imidacloprid is highly effective against most sucking pests belonging to Hemiptera,[70] fleas in Siphonaptera,[71] some beetle species in Coleoptera,[72] but also is toxic to Hymenoptera including honeybees[73,74] and parasitoid wasps.[75] However, the modest physiological selectivity of imidacloprid can be improved through ecological selectivity that is gained by using imidacloprid as a soil application for systemic uptake by treated plants. This avoids the use of foliar sprays and the potential for contact with any insect in the plant canopy, pest or beneficial. Apart from the risk to pollinators or other beneficial species that gather pollen or feed on nectar and plant sap,[76] exposure to systemic imidacloprid in plants should principally involve pests that feed on the plants along with the occasional omnivorous predator.

From an IPM practitioner's standpoint, immediate interest in insecticide selectivity is focused more narrowly on Arthropoda, mainly on class Insecta. The principal interest is whether a given treatment will be physiologically selective to a resident pest infestation without also obliterating the natural enemies attending that pest. While the potential exists for making a selective application of an insecticide, there can be distinct advantages to being able to use a physiologically selective insecticide without the constraints that may be involved with a selective application. For example, if a lower dose application against the pest infestation is not feasible due to resistance or naturally higher tolerance compared to natural enemies, then using a selective insecticide could provide the needed control of the pest while retaining a healthy proportion of natural enemies to continue with suppression once residual activity of the treatment subsides. The availability of an option to use a selective insecticide while conserving natural enemies relative to a non-selective insecticide provides a valuable management tool to the well-informed pest manager.

As pointed out by Stern *et al*.,[3] chemical treatments represent only temporary suppression of a localized population that invariably rebounds unless met with environmental resistance. Their discussion on the general equilibrium position was instructive of the tendency of a pest population forced well below its equilibrium position to return to, and possibly, exceed that position if biological control had been decimated by the same chemical treatment. Hence, the requirement for selective insecticides that exert greater suppressive power against the pest population relative to natural enemy populations was viewed as essential to maintaining environmental resistance, and ultimately fostering the integration of biological and chemical control.

More recently, a series of studies[77–81] conducted in Arizona cotton have demonstrated the principle of sustaining environmental resistance following insecticide treatments directed against the whitefly pest *B. tabaci*. Prior to the introduction in 1996 of two insect growth regulators (IGRs), buprofezin and pyriproxyfen, insecticide treatments for *B. tabaci* as the primary pest in cotton grown in the southwestern USA had been dominated by organophosphate-synergized pyrethroids. But these failed in 1995 in the intensive cotton producing areas of central Arizona due to resistance,[82] thereby paving the way for emergency registration of the two IGRs. Life table studies featuring mortality assessments of sessile *B. tabaci* nymphs were conducted *in situ* and revealed a high degree of selectivity for buprofezin and pyriproxyfen. This conclusion was based on significantly higher levels of predation in the IGR plots relative to conventional insecticide-treated plots, especially in the weeks following initial application. The persistence of predators following initial treatments with IGRs and an overall reduction in insecticide use for whiteflies[60] resulted in fewer follow-up treatments compared to conventional insecticide-treated plots. This finding in particular gave rise to the terminology 'bio-residual',[78,79] which in many ways is akin to the environmental resistance provided by natural enemies and other regulating factors referred to by Stern and colleagues[3].

The success of the IGR-based IPM program in Arizona cotton[60] reinforced the importance of effective timing of IGR applications for prolonged control of *B. tabaci*. By positioning the IGRs within Stage I chemistry, not only were beneficial insects conserved to make possible the bioresidual effect, but the demographic structure of the early-stage infestation of whiteflies was biased towards eggs and early instar nymphs, the stages most vulnerable to pyriproyfen and buprofezin, respectively. The proper timing of an insecticide application with respect to environmental conditions,[83] pest phenology,[84,85] and avoidance of beneficial insects[86,87] has always been considered important to the success of a treatment. With some of the newer selective insecticides that interfere with insect development, the demographic makeup of the target population may also be another important consideration in the timing of applications.[88,89] There are now six different insecticide modes of action that affect growth or development of one or more orders of insects or mites.[90]

With the development of newer, more selective modes of action in recent decades, there are excellent opportunities for devising more integrative IPM programs for a wide spectrum of pest species. These should be built on the concept that any necessary insecticide treatments will provide effective control of the pest population in the short term, and that good bio-residual activity will continue to provide the environmental resistance that limits the need to treat repetitively. This will require thorough knowledge of the cropping system to understand the key pest and natural enemy species, when they occur in the crop, and what the relative toxicity profiles are for candidate insecticides, so that a well-timed, compatible system can be put together to attain biological and chemical integration. For example, the pyriproxyfen treatment that continues to be used so successfully in Arizona cotton against *B. tabaci* has been suspected of causing pest upsets in citrus where coccinellid beetles are a principal predator species.[91–93] Variable success of a particular compound in terms of compatibility with different natural enemy species highlights the need to know the system and the impact that each treatment has on pest and beneficial species alike. The design and integration of biological and chemical control agents is complex and knowledge-intensive, requiring well-informed practitioners with a sense of the ecosystem and the role it plays in maintaining population balances.[3]

4 IPM SUSTAINABILITY

The intensification of agricultural systems over time has altered environments to make them more conducive to pest populations.[3,94,95] Expansion of crop acreages driven to high rates of growth through optimal water and fertilizer inputs have created ideal food resources for rapidly colonizing species of phytophagous insects. Intensified crop conditions have prevailed in numerous situations where destructive pest outbreaks have occurred or where previously unimportant species have elevated to pest status. In their insightful perspective Stern *et al.*[3] pointed to the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), and the alfalfa butterfly, *Colias philodice eurytheme* Boisduval, as previously insignificant members of the natural fauna that had risen in pest status as potatoes were brought under widespread cultivation in the United States, or following the introduction of alfalfa to California around 1850. The shifts in general equilibrium position due to vastly increased food resources is apparent for both pests, yet this consideration has too often been left out of discussions implicating pesticides as the cause of outbreaks for other pest species. While it is often convenient and popular to point to insecticide resistance and pesticide-induced disruption of biological control as principal causes of pest outbreaks, underlying components and processes in the agroecosystem also play significant roles in population dynamics of pests and their natural enemies.[1] Developing a better understanding of agroecosystems in general, but also a specific knowledge of individual systems, will enable more creative and holistic solutions for pest problems to be developed with reduced dependence on chemical control.

Loss of insecticide efficacies due to resistance occurs under normal pest pressure as well as during outbreak situations when insecticide treatments can increase dramatically.[78] The problem is that even modest insecticide use can lead to resistance as quantitative changes in resistance gene frequencies occur under varying selective regimes.[96] A gradual loss of efficacy due to resistance may induce pest managers to seek more severe remedies that are less compatible with biological control and ultimately disruptive of IPM programs. Development of resistance management strategies should therefore be a foremost consideration in the design and sustainability of IPM programs. The basic principles of managing resistance have been presented in numerous review articles and book chapters and widely disseminated among pest management practitioners.[97,98] The challenge is to integrate these principles to the fullest extent within pest management programs that limit reliance upon chemical control. Although each cropping system will have unique challenges, there are three basic rules that should, in principle, have universal application. The first is to minimize insecticide use by employing all conceivable non-chemical modes of control. This was exactly the intent of the integrated control concept, i.e. to refrain from insecticide treatments by using biological control and other forms of environmental resistance to prevent economic infestations from building. The second rule is to diversify insecticide use if multiple applications become necessary. Rotating among insecticide classes has long been recommended for reducing selection pressure on any one mode of action. The proliferation of new modes of action over the past two decades has made it possible in many cropping situations to devise an insecticide use strategy where no single mode of action is used more than once per cropping season or even per year. However, a risk of losing insecticide selectivity is incurred by having to resort to more than one application in a rotation scheme. This is where an insecticide use plan can be useful to avoid the overlapping of different modes of action, but also to preserve selectivity in the treatment regime by preferentially using those insecticides with higher selectivity. By anticipating pest infestations based on experience and knowledge of pest dynamics, conscientious pest managers could develop provisional treatment plans for an entire cropping year. An insecticide deployment schedule could then be superimposed that would minimize overlap in modes of action while maximizing effectiveness of each insecticide application. Actual treatments would of course rely solely on thresholds and scouting information that justify treatment action, but the preplanned schedule would provide a structural framework for avoiding repetitious use of a single mode of action. Finally, the third rule of managing insecticide resistance should be to refine insecticide use to become more compatible with biological control. This is not only a process of choosing selective insecticides that will have minimal impact on beneficial insects, but also incorporating rigorously defined thresholds and sampling plans to avoid unnecessary treatments. While these are also elements of good IPM, they more specifically relate to responsible use of insecticides.

A history of breakdowns in pest management has invariably been related to chemical control problems that became progressively worse due to resistance and/or disruption of natural enemy populations. Historical and current focus on chemical control as the linchpin of IPM sustainability is therefore not unwarranted. However, equal emphasis must be placed on other control components of an IPM program, including biological and cultural controls, if not because they are at equal risk as chemical control, then because they must play as significant a role in a balanced, sustainable program. The Stern *et al.*[3] focus on conservation of natural enemies was primarily based on reducing disruption by insecticides, but a wealth of research has and is addressing habitat modification to enhance natural enemies both inside and outside the crop as a method to promote more effective biological control.[99,100] In addition, much more information on how natural enemies are being affected by reduced-risk, and other newly introduced insecticides, is needed to continue tailoring integrated control approaches that are most compatible. Regarding cultural control, strategic planning akin to what was recommended for diversifying insecticide use through crop seasons must be implemented with respect to crop rotations and placement, especially for mobile and polyphagous pests. For example, sequential crops planted in close proximity to one another and which are colonized by the same polyphagous pest are an example of poor planning that can exacerbate pest infestations. However, in the case of a monophagous pest, the first crop may serve as an important source of natural enemies for the second crop. The finessing of cultural methods of control was much more common prior to the advent of synthetic organic insecticides.[1] The requirement for creative pest control solutions on the farm diminished once the chemical age dawned, but now should be reconsidered in the interest of promoting non-chemical control practices and agricultural sustainability.

5 FINAL THOUGHTS

The knowledge base and toolset necessary for IPM programs have grown tremendously in the last three decades, making integration of biological and chemical control in the spirit of Stern and colleagues[3] more feasible than ever before. However, transition to more selective insecticides has been gradual as moderate to heavy dependency on broad-spectrum insecticides continues in many crop systems. Numerous factors account for the possible reluctance to shift to the newer insecticides, including higher costs, a need for more individual pest species decisions rather than a single pest-spectrum decision, and greater uncertainty about how some of the newer modes of action actually work against target populations. For selective insecticides that disrupt developmental pathways, there are additional complications in that demographic information about the pest infestation should be obtained before making an application. This means that a sampling plan ideally is required to make sophisticated appraisals of the structure of insect pest populations. All of this adds up to a level of knowledge that is not available for many cropping systems and pest complexes and illustrates the degree of rigor required to carry out informed IPM programs. Obtaining sufficient command and know-how to conduct knowledge-based IPM can be an intimidating prospect and may in part be responsible for the failure of IPM to be more widely adopted.[18]

Ironically, one of the traditional sources of agricultural knowledge and training, the land-grant universities in the USA, have in recent years shifted declining resources away from agricultural to more biotechnological applications. The impact of such reallocation is that the number of academic positions occupied by agriculturalists has severely declined, as have the academic programs responsible for training professional consultants who carry out pest management decisions in the field. Fifty years after Stern and colleagues[3] introduced the integrated control concept, the classical transfer of knowledge from university to the field is being undermined with uncertain consequences for pest control in the future. The essential requirement for a knowledge-driven management approach implicit in the integrated control concept is perhaps even more urgent for today's agriculture to meet world demands for food and fiber. Informed and Integrated Pest Management represents the path that must be followed to develop the comprehensive and sustainable pest management strategies that will meet these demands while minimizing impact to the environment.

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