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Perspective

A total system approach to sustainable pest management

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ABSTRACT A fundamental shift to a total system approach for crop protection is urgently needed to resolve escalating economic and environmental consequences of combating agricultural pests. Pest management strategies have long been dominated by quests for "silver bullet" products to control pest outbreaks. However, managing undesired variables in ecosystems is similar to that for other systems, including the human body and social orders. Experience in these fields substantiates the fact that therapeutic interventions into any system are effective only for short term relief because these externalities are soon "neutralized" by countermoves within the system. Long term resolutions can be achieved only by restructuring and managing these systems in ways that maximize the array of "built-in" preventive strengths, with therapeutic tactics serving strictly as backups to these natural regulators. To date, we have failed to incorporate this basic principle into the mainstream of pest management science and continue to regress into a foot race with nature. In this report, we establish why a total system approach is essential as the guiding premise of pest management and provide arguments as to how earlier attempts for change and current mainstream initiatives generally fail to follow this principle. We then draw on emerging knowledge about multitrophic level interactions and other specific findings about management of ecosystems to propose a pivotal redirection of pest management strategies that would honor this principle and, thus, be sustainable. Finally, we discuss the potential immense benefits of such a central shift in pest management philosophy.

The therapeutic approach of killing pest organisms with toxic chemicals has been the prevailing pest control strategy for over 50 years. Safety problems and ecological disruptions continue to ensue (1), and there are renewed appeals for effective, safe, and economically acceptable alternatives (2). Considerable effort has been directed toward such alternatives, and new technology has been implemented and is still emerging. However, the major trend has been toward the use of modern chemistry and molecular biology to replace traditional pesticides with less hazardous chemicals or nontoxic biologically based products; but these means are still therapeutics. Thus, the classic treadmill effect in pursuit of remediation of the symptoms persists (2) while tolls due to pests grow higher by some estimates. Crop losses due to arthropods, diseases, and weeds, though disputed by some as a valid measure, have increased on a world basis from 34.9% in 1965 (3) to 42.1% in 1988–1990 (4) despite the intensification of pest control.

In this report, we argue that the central weakness in how we think about pest management as a component of agricultural systems has not been addressed. We must go beyond replacing toxic chemicals with more sophisticated, biologically based agents and re-examine the entire paradigm around the therapeutic approach, including how and why those therapeutics are used. Truly satisfactory solutions to pest problems will require a shift to understanding and promoting naturally occurring biological agents and other inherent strengths as components of total agricultural ecosystems and designing our cropping systems so that these natural forces keep the pests within acceptable bounds. Recent discoveries in multitrophic interactions (5) together with renewed emphasis on broader based ecosystem management (6) indicate powerful prospects for this direction. Although we address the subject primarily from a perspective of arthropod pests, similar cases can generally be made for other pests [see Cook *et al.* (7) for background information important to related views for other pests].

Premise of a Revised Approach

The underlying principle of our position is that components of agricultural ecosystems interact, and, through a set of feedback loops, maintain "balance" within functional fluctuating bounds. Furthermore, therapeutic interventions into these systems are met by countermoves that "neutralize" their effectiveness [see Flint and van den Bosch (8) and Cook and Baker (9) for an elegant discussion of this point]. We are taught this basic principle from our earliest training in ecology but often overlook it in practice for various reasons, including our tendency in science to divide things into specialized parts, i.e., to apply a reductionist approach. The basic principle for managing undesired variables in agricultural systems is similar to that for other systems, including the human body and social systems. On the surface, it would seem that an optimal corrective action for an undesired entity is to apply a direct external counter force against it. However, there is a long history of experiences in medicine and social science where such interventionist actions never produce sustainable desired effects. Rather, the attempted solution becomes the problem [See Waltzlawick *et al.* (10) for a discussion of this subject with coverage of underlying mathematical principles.] We find vivid examples to this end in the problems of addiction as a consequence of the use of drugs for treatment of pain or mental distress and black market crime as a repercussion to the use of prohibition as an intended solution for alcoholism. Thus, as a matter of fundamental principle, application of external corrective actions into a system can be effective only for short

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Abbreviations: IPM, Integrated Pest Management; Bt, *Bacillus thuringiensis*.

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term relief. Long term, sustainable solutions must be achieved through restructuring the system so that inherent forces that function via feedback mechanisms such as density dependence are added and/or function more effectively.

The foundation for pest management in agricultural systems should be an understanding and shoring up of the full composite of inherent plant defenses, plant mixtures, soil, natural enemies, and other components of the system. These natural "built in" regulators are linked in a web of feedback loops and are renewable and sustainable. The use of pesticides and other "treat-the-symptoms" approaches are unsustainable and should be the last rather than the first line of defense. A pest management strategy should always start with the question "Why is the pest a pest?" and should seek to address underlying weaknesses in ecosystems and/or agronomic practice(s) that have allowed organisms to reach pest status.

Attempts for Change: No Real Change

Throughout the debate on alternative methods for controlling pests, various ideas have been expressed and new approaches have emerged. Three subject areas, Biological Control, Integrated Pest Management (IPM), and Biotechnology, have achieved particular importance in our quest for better pest control strategies.

Biological Control. Biological control has a long history of use in pest management and has gained renewed interest because of problems encountered with the use of pesticides. The term "biological control" has been used, at times, in a broad context to encompass a full spectrum of biological organisms and biologically based products including pheromones, resistant plant varieties, and autocidal techniques such as sterile insects. The historical and more prevalent use of this term is restricted to use of natural enemies to manage populations of pest organisms.

Biological control has been spectacularly successful in many instances, with a number of pest problems permanently resolved by importation and successful establishment of natural enemies. These importation successes have been limited largely to certain types of ecosystems and/or pest situations such as introduced pests in perennial ecosystems. On the other hand, this approach has met with limited success for major pests of row crops or other ephemeral systems. In these situations, the problem is often not the lack of effective natural enemies but management practices and a lack of concerted research on factors that determine the success or failure of importation attempts in the specific agroecosystem setting. Thus, importation programs, to date, are largely a matter of trial and error based on experience of the individual specialists involved.

Conservation of natural enemies received more attention as part of a cultural management approach before the advent of synthetic pesticides. Since that time, this realm of biological control has been neglected. The term "conservation" tends to limit one's vision to a passive approach of acknowledging that natural enemies are valuable and should be harmed no more than necessary. It is important that we develop a more active approach that seeks to understand natural enemies and how they function as a part of the ecosystem and to promote their effectiveness by use of habitat management (landscape ecology) and other cultural management approaches.

Augmentation through propagation and release of natural enemies is an area of biological control that has received much attention in recent years. These efforts include research on *in vitro* and *in vivo* mass rearing technology and on transport and release methodology for area-wide population suppression and for field-to-field therapeutic treatments. Although the development of this technology is valuable, it is an extension of the treat-the-symptoms paradigm. In principle, natural enemies used in these methodologies are biopesticides, and the general approaches differ from conventional pesticidal applications only in the kind of products used. From this "product formulation" perspective and from our existing infrastructure, the major emphasis in augmentation schemes becomes focused on how to produce and transport a large number of natural enemies at a low cost. Less emphasis is placed on how natural enemies function and how we can promote their natural effectiveness.

In keeping with the historical therapeutic-based attitude and existing infrastructure, most concentrated efforts for biological control appear to be directed toward the "rear and release" augmentation, followed by importation and thirdly by conservation. This order of priorities should be reversed. First, we need to understand, promote, and maximize the effectiveness of indigenous populations of natural enemies. Then, based on the knowledge and results of these actions, we should fill any key gaps by importation. Finally, therapeutic propagation and releases should be used as a backup to these programs when necessary.

IPM. Throughout our quest for alternative pest control measures, the IPM concept has by far received the most attention as a comprehensive pest management approach. IPM has had a varied history, has been defined in many ways, and has been implemented under an array of different connotations. The term was first used as "integrated control" by Bartlett (11) and was further elaborated on by Stern *et al.* (12) in reference to the concept of integrating the use of biological and other controls in complementary ways. The term was later broadened to embrace coordinated use of all biological, cultural, and artificial practices (13). Subsequently, under the term "IPM," various authors have advocated the principle of incorporating the full array of pest management practices together with production objectives into a total systems approach. See Flint and van den Bosch (8) for a comprehensive and ecologically based discussion of this concept and the potential benefits of its implementation.

The principles discussed by Flint and van den Bosch (8) are, in our opinion, solid and on target. They make a thorough case for a comprehensive long term pest management program based on knowledge of an ecosystem that weighs economic, environmental, and social consequences of interventions. However, as translated into practice, IPM has been primarily a monitoring program in which thresholds are established and chemicals are used only on an as-needed basis. Much less emphasis has been placed on understanding and promoting inherent strengths within systems to limit pest populations through use of approaches such as landscape ecology. In other words, IPM programs have been operated with pesticide management objectives rather than pest management objectives. We hasten to add that their use has been of major benefit and has greatly reduced the quantity of pesticides used. Furthermore, activities remain underway to refocus IPM toward the achievement of its full objectives (14, 15). However, our point is that, again, the tendency has been to remain centered on a monitor and treat-the-symptoms approach vs. the more fundamental question of "Why is the pest a pest?"

Biotechnology. Although biotechnology is not a pest management approach as such, we include it because it is receiving major emphasis and is being geared to provide a wave of new products for pest management. In fact, many seem to view biotechnology as an innovative means for providing safe and effective tools that will essentially resolve pest management problems. Major technological advances in chemistry, biochemistry, behavior, neurophysiology, molecular genetics, and genetic engineering have resulted in an array of biorational products and materials that are less toxic and hazardous to humans and the environment than conventional pesticides. These products include genetically engineered plants for stronger resistance to pests, plants, and natural enemies with high tolerance to pesticides and sophisticated formulations and delivery methods for biopesticides, semiochemicals, and other new tools. The biorational/biologically based materials provided are potentially valuable advancements that have an appropriate place in modern pest management. However, the strategy for development and use of these "high tech" tools has been dominated by a continued search for "silver bullet" solutions that can be easily deployed in a prescription-like manner to remediate pest outbreaks or to exclude the pest's presence. As spectacular and exciting as biotechnology is, its breakthroughs have tended to delay our shift to long term, ecologically based pest management because the rapid array of new products provide a sense of security just as did synthetic pesticides at the time of their discovery in the 1940s. Also, industry focuses on using genetic manipulation and other techniques to increase the virulence and host range of biopesticides instead of designing them as complements to natural strengths. Thereby, the manipulated pathogens and the crops engineered to express toxins of pathogens are simply targeted as replacements for synthetic pesticides and will become ineffective in the same way that pesticides have. It will be unfortunate if these powerful agents are wasted rather than integrated as key parts of sustainable pest management systems.

New Direction

The four major problems encountered with conventional pesticides are toxic residues, pest resistance, secondary pests, and pest resurgence. The latter three of these are fundamental consequences of reliance on interventions that are both disruptive and of diminishing value because of countermoves of the ecological system. Therefore, a mere switch to nontoxic pesticides, such as microbials or inundative releases of natural enemies, although helpful in reducing environmental contamination and safety problems, still does not truly address the ecologically based weakness of the conventional pest control approach. Such tools used in this manner, whether chemical, biological or physical, are extensions of the conventional approach that leaves us in a confrontation with nature. Also, this operational philosophy tends to promote the development and adoption of the more disruptive products because, within this paradigm, they work better than softer, less obtrusive materials.

What, then, would represent a meaningful fundamental shift in our pest management strategy? Furthermore, what should be the components of such a strategy, and how can we crystallize this strategy into programs that result in effective and lasting pest management systems? Clearly, the central foundation should be approaches that appreciate the interactive webs in ecosystems and seek solutions with net benefits at a total ecosystem level. Therefore, the approaches should focus on harnessing inherent strengths within ecosystems and be directed more toward bringing pest populations into acceptable bounds rather than toward eliminating them (Fig. 1). These solutions would avoid undesirable short term and long term ripple effects and would be sustainable. Moreover, for adoption of such approaches, they must reasonably meet production demands and be cost-competitive on the short term. We suggest three lines along which approaches can be developed: (*i*) ecosystems management; (*ii*) crop attributes and multitrophic level interactions; and (*iii*) therapeutics with minimal disruptions. However, with all of these approaches, it is important to keep in mind the objective of balance vs. undue selective pressure by any single tactic. Recent experiences with insect pest management for cotton in the southeastern United States will be used for key examples in the discussion.

Ecosystem Management. Understanding and managing an ecosystem within which we farm is the foundation upon which all the farming strategies, including pest management, should be designed. This foundation has become the victim of reductionist approaches. Because of political and funding channels, scientific teams typically are assembled around commodities across geographical areas. Therefore, the informational base relative to a particular crop as an interactive component of a farming ecosystem is very limited. For example, cotton specialists focus their interactions toward other cotton specialists, often within their own discipline, across the cotton belt. However, both vegetable and cotton production are increasing in the same area and sometimes on the same farms in the southeastern United States. These crops share many of the same pests and natural enemy fauna. Therefore, pest management practices on one crop can directly or indirectly affect the other. A redirection of pest management is needed to incorporate year-round soil, weed, cropping, water, and associated practices at farm and community levels and to consider the effects of these practices on the overall fauna, nutritional state, and balance of local ecosystems (16).

Recent studies demonstrate that such a redirection would be highly fruitful. For example, problems with soil erosion have resulted in major thrusts in use of winter cover crops and conservation tillage. Preliminary studies indicate that cover crops also serve as a bridge/refugia to stabilize natural enemy/pest balances and relay these balances into the crop season (17, 18). Crimson clover and other legumes, into which cotton can be strip tilled in the Southeast, appear to be good winter and spring reservoirs for predators and parasitoids of cotton pests

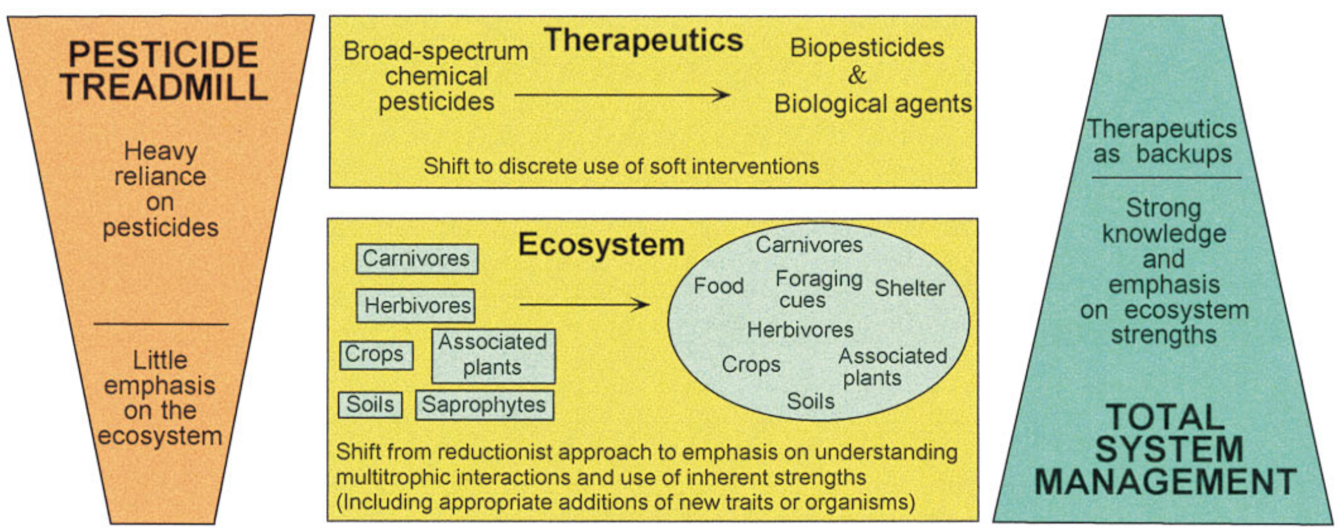

FIG. 1. Illustration of a shift to a total system approach to pest management through a greater use of inherent strengths based on a good understanding of interactions within an ecosystem while using therapeutics as backups. The upside-down pyramid to the left reflects the unstable conditions under heavy reliance on pesticides, and the upright pyramid to the right reflects sustainable qualities of a total system strategy.

(19, 20). The green cloverworm in clover serves as a good alternate winter and spring host for the parasitoid *Cotesia marginiventris* that limits subsequent outbreaks of armyworms and loopers in the cotton (21). Also, aphid, thrips, and budworm/bollworm populations in clover appear to provide reservoirs for establishing earlier balances between these pests and their natural enemy guilds. On the other hand, when fields are fallow during winter and spring, natural enemy buildups cannot begin until a crop is available. Integrating appropriate cover crops with conservation tillage can have a number of agronomic benefits: reduced soil erosion, enhanced levels of organic matter, improved soil drainage and moisture retention, restoration of important nutrients, and weed control (20, 22, 23) while restoring and strengthening natural pest control. Other preventive measures including crop rotations, avoiding large scale monocropping, leaving unsprayed strips, and planting field margins with appropriate year-round refugia for natural enemies will contribute to prevention of pest outbreaks (24–26).

The growing of clover and/or encouragement of certain weeds along field margins and other unplanted areas can also provide important refugia for developing natural enemy/pest balances during a cropping season. For example, two common weeds in the southeast, fleabane and horsetail, are important hosts for plant bugs and their natural enemies. In fact, they are preferred over cotton by the insects, and data indicate that these plants act as effective decoys to coax plant bugs away from cotton (19). Serious infestations of plant bugs occur primarily where cotton is planted "ditch bank to ditch bank," along with clean cultivation apparently caused by exclusion of such preferred alternate host plants.

Obviously landscape ecology practices exert a variety of desired or undesired effects on cropping systems (27). Thus, it is vital that we assemble appropriate teams to elucidate interactions at the ecosystem level to establish the knowledge base for ecologically based pest management systems.

Crop Attributes and Multitrophic Level Interactions. Consideration of crop plants as active components of multitrophic level interactions is crucial to a total systems approach to pest management. We have known vaguely for a long time that plant traits have important impacts on both herbivores and their natural enemies. But, again, the reductionist approach has caused us to manipulate plant traits in ways detrimental to long term balance in the cropping systems.

Recent discoveries of tritrophic level interactions among plants, herbivores, and parasitoids/predators have demonstrated how tightly interwoven these components are and illustrate the importance of multitrophic perspectives for effective and sustainable pest management strategies. Plants have long been known to possess toxins and other chemicals that serve to discourage herbivore feeding. The discipline of host–plant resistance directed toward breeding plants resistant to pest attack was developed around such knowledge and contributed greatly to pest management. Recent studies also show, however, that plants play an active and sophisticated role in their defense against insect activities, and their defense responses often are customized for certain, interactive, multitrophic situations (5). For example, some plants respond to insect herbivory by releasing volatile chemical cues that attract predators and parasitoids that, in turn, attack the herbivores (28–30). These volatiles are released only in response to herbivore damage, not by mechanical damage similar to herbivory, and are released from the entire plant (31, 32). This effect enables the natural enemy to distinguish infested plants from uninfested neighbors. For example, cotton fed on by beet armyworm larvae releases terpenoids that attract the parasitoid *C. marginiventris.* Furthermore, a certain naturalized variety of cotton releases ≈10 times more of these chemicals in response to the insect herbivore damage than do commercial lines (33). By understanding the mechanisms governing such important defense attributes, they can be restored to domestic cultivars, and their incidental loss, while breeding for other traits, can be prevented in the future.

Crop plants also provide vital food resources for certain key natural enemies. Floral and extra floral nectaries, for example, provide necessary food for foraging parasitoids. Extra floral nectar increases the attraction, efficiency, and retention of the key parasitoids *C. marginiventris, Microplitis croceipes*, and *Cardiochiles nigriceps*, important to the control of armyworms and bollworms/budworms in crops such as cotton (34, 35). However, extra floral nectar also serves as food for certain pests such as the adult moths of the caterpillar pests just mentioned. Based on information regarding the role of the extra floral nectar as food for moths, nectariless cotton varieties were released a few years ago without regarding their importance as a food for natural enemies of cotton pests. These facts emphasize the need to broaden our base of information upon which we design pest management strategies.

Also, there is a rapidly expanding body of knowledge about similar signaling that enables injured plants to produce toxins and antifeedants that are directed specifically toward herbivores. For example, feeding activities of certain caterpillars on the leaves of tomatoes and potatoes induce a systemic production of protease inhibitors expressed throughout the plant that interfere with the digestion process and feeding behavior of insects (36).

Even greater than our limited knowledge of the mechanisms regulating these important plant attributes is the void in our knowledge of how factors like soil properties, nutrition, and/or water stress affect their expression. Inadequate availability of a key soil element for example could make a major difference in the effectiveness of one or more of a plant's interactions with herbivores or natural enemies, thereby influencing a plant's vulnerability to herbivore damage in a major way. Greater understanding of the factors that regulate these interactions in cropping systems can allow us to deal with plant health at an entirely different level.

There is a tendency within the traditional paradigm to use toxins, attractants, or other plant attributes as products and to intervene in ways that are out of harmony with natural system interactions. For example, we identify, synthesize, and formulate herbivore toxins and natural enemy attractants as sprays to kill herbivores and lure the natural enemies, respectively. Also, we breed and engineer plants for constitutive expression of traits in ways that maximize immediate deterrence of pests or attraction of natural enemies without regard to pest density or plant damage. Natural systems provide evidence that this is not always an appropriate approach for plant defense. In the case of the protease inhibitor in tomato and potato cited above, these materials are constitutively expressed in the fruit but only induced by damage in leaves (37). We suggest that this system has been selected in nature because it is the most durable strategy. A system of constitutive expression in fruit but only inducible in leaves experiencing damage by feeding insects provides maximum protection of the fruit. Leaves serve as a decoy alternative for feeding by caterpillars but possess a mechanism that limits feeding damage. This strategy also provides host/prey resources that allow participation by a plant's parasitoid/predator allies. We must observe and consider natural systems when developing strategies for novel traits such as a gene for producing *Bacillus thuringiensis* (Bt) toxin, i.e., plant engineering [see Gould (38) for an excellent reference in this regard]. For example, cotton cultivars with a full constitutive expression of Bt toxin have been introduced commercially. This practice amounts to a continuous spraying of an entire plant with the toxin, except the application is from inside out. Various methods for resistance management, including pest/natural enemy refugia and limiting acreage planted with a cultivar, are being used. However, we urge more concerted efforts toward breeding and engineering plants with traits such as tissue-specific and damage-induced chemical defenses that work in harmony with natural systems.

Genetic engineering and other such technologies are powerful tools of great value in pest management. But, if their deployment is to be sustainable, they must be used in conjunction with a solid appreciation of multitrophic interactions and in ways that anticipate countermoves within the systems. Otherwise, their effectiveness is prone to neutralization by resistance in the same manner as with pesticides.

Therapeutics. Therapeutics have a valuable role in ecologically based pest management strategies, but they should be viewed as backups rather than as primary lines of defense. Also, therapeutics should be recognized as potentially disruptive and used as unobtrusively as possible. The key principle is that they should be geared toward bringing a pest organism into acceptable bounds with as little ecological disruption as possible. Synthetic products, natural products, and living organisms can be effective as therapeutics, and the fact that a product is natural and/or nontoxic does not necessarily mean it is less disruptive than synthetic products. The important thing is to work as much in harmony as possible with the system's inherent defenses.

A wide array of therapeutic products are available, and more are being developed with modern technology. A vast arsenal of natural products identified from plants, insects, and microorganisms is being synthesized and formulated for use as biopesticides. Semiochemicals such as sex pheromones and natural enemy attractants can be used as baits and lures to disrupt pest activity and promote natural enemy presence. Pathogens, parasitoids, as reared *in vivo* or *in vitro*, are available and are being touted as therapeutic tools. All of these organisms and/or their by-products are important biofriendly alternatives to toxic, broad spectrum, conventional pesticides. Still, our primary pest management tactic should be maximization of built in pest reduction features of an ecosystem. Therapeutic tools should be used as secondary backups. Overreliance on them will return pest management strategies to a treadmill situation (Fig. 1).

Another problem is the tendency to seek therapeutics that give us the quickest effect. Sales of biological insecticides amount to about $110 million annually, and Bt is the main product ($90 million). Generally, microbial organisms work slowly relative to synthetic pesticides. Therefore, industry has as first priority formulation of microbials to obtain faster kill and is less interested in long term pest reduction effects. Thus, the role that microbials could play in orchard and forest pest management, as well as in programs like control of grasshoppers in Sahelian, Africa, is neglected (39).

Retarded development of pests may be more desirable than quick kill in certain situations. For example, Bt products are considered unacceptable for controlling beet armyworms in cotton because of their slow killing action. Yet, some studies indicate that a slow kill may be more preferable when examined from a larger perspective. As indicated above, *C. marginiventris* is a key parasitoid for managing the beet armyworm and interventions should avoid disrupting this natural enemy. Beet armyworm larvae intoxicated by sublethal dosages of MVP (Mycogen, San Diego) (a Bt-derived biopesticide) experience retarded development and feeding and are subject to higher parasitism than nontreated beet armyworm larvae (40). In other words, an effective, nondisruptive way to manage a moderate beet armyworm outbreak may be to retard its development and damage while giving the parasitoids time to work, thereby strengthening the parasitoids' effect during subsequent generations. A similar effect was reported earlier for Bt and a parasitoid of gypsy moths (41). A quick kill may provide more immediate results but destroys a resource for parasitoids and limits their presence with subsequent generations of pests, thus leading to resurgence.

We must remember—our primary objective in pest management is not to eliminate a pest organism but to bring it into acceptable bounds. The role of therapeutics is not to replace natural systems. Rather, their role is to serve as complements while the system is temporarily out of balance. From that perspective, it is clear that interventions that interfere with the restoration of balance are counterproductive. Waage (39) suggests that biopesticides could form the "methadone of IPM," helping agroecosystems to recover from the habit of calendar spraying while we are redesigning and nurturing them to a more self-renewing capacity.

Potential Benefits

The benefits of a total system approach would be immense, directly to farming and indirectly to society. The approach takes into account impacts on our natural resources such as the preservation of flora and fauna, quality and diversity of landscape, and conservation of energy and nonrenewable resources. Long term sociological benefits would also emerge in areas of employment, public health, and well being of persons associated with agriculture (42, 43).

In The Netherlands, prototypes of various multidisciplinary, arable farming systems have been evaluated on a semipractical scale (44). In 1979, a national experimental farm for the development and comparison of alternative farming systems was set up in Nagele (one of the "polders"). The size of the farm was 72 hectares (almost 300 acres). Among other studies, integrated and conventional farming practices were compared for seed potatoes, dry peas, carrots, onions, sugar beets, and winter wheat. Crop protection and other management practices with the integrated approach followed the basic principles discussed herein.

Over a 15-year period, pesticide use on these integrated farms was reduced over 90% (Fig. 2). They found that pesticides, and fertilizers, can be decreased through implementation of alternative practices based on intensified knowledge of the ecosystem. Artificial fertilizers are replaced by organic manure and effective use of crop residues. Insect, weed, and disease problems are reduced through natural control by the enriched natural enemy fauna, the use of weed-competitive or disease- and pest-resistant varieties (with an emphasis on durable systems for resistance), reduction of nitrogen fertilization, and judicious use of chemical pest control based on careful population sampling and decision thresholds. Results from these demonstration farms have been so encouraging that implementation of integrated farming is being enforced by the

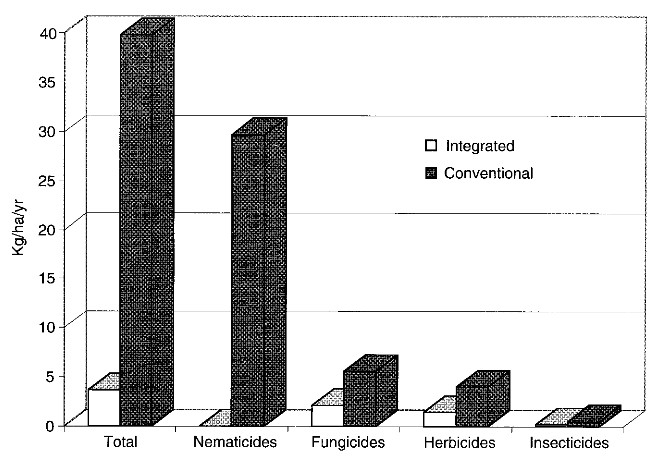

FIG. 2. Average use of pesticides (kilogram active ingredient/hectare/year) in conventional and integrated farming demonstrations in The Netherlands (1986–1990); after Wijnands and Kroonen-Backbier (43). ha, hectare.

Dutch Ministry of Agriculture to reduce environmental pollution and to create a firmer basis for survival of agriculture in the longer term.

Yields were somewhat lower on the demonstration farms but were compensated for by cost reduction through lower pesticide and fertilizer inputs. Thus, the net short term profits of the demonstration farms were equal to those of the conventional farms. We emphasize the short term economic aspect of sustainable farming because immediate profitability figures, along with the environmental concerns, are crucial to adoption of the practices. However, the eventual consequences of conventional farming are so severe, environmentally, socially, and economically, that it is wise to initiate changes even under situations in which short term economic benefits are marginal. Bio-friendly agriculture and good economics, over the long term, clearly go hand in hand.

CONCLUSION

Recent quests for effective, safe, and lasting pest management programs have been targeted primarily toward development of new and better products with which to replace conventional toxic pesticides. We assert that the key weakness with our pest management strategies is not so much the products we use but our central operating philosophy. The use of therapeutic tools, whether biological, chemical, or physical, as the primary means of controlling pests rather than as occasional supplements to natural regulators to bring them into acceptable bounds violates fundamental unifying principles and cannot be sustainable. We must turn more to developing farming practices that are compatible with ecological systems and designing cropping systems that naturally limit the elevation of an organism to pest status. We historically have sold nature short, both in its ability to neutralize the effectiveness of ecologically unsound methods as well as its array of inherent strengths that can be used to keep pest organisms within bounds. If we will but understand and work more in harmony with nature's checks and balances we will be able to enjoy sustainable and profitable pest management strategies, which are beneficial to all participants in the ecosystem, including humans.

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