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Weed Science Beyond the Weeds: The Role of Integrated Weed Management (IWM) in Agroecosystem Health[1]

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Abstract. **Integrated weed management (IWM) research has focused on how crop yields and weed interference are affected by changes in management, e.g., tillage, herbicide application timing and rates, cover crops, and planting patterns. Acceptance of IWM will depend on recommendation of specific strategies that manage weeds and maintain crop productivity; such research will and should continue. However, IWM needs to move from a descriptive to a predictive phase if long-term strategies are to be adopted. Linking management changes with crop-weed modeling that includes such components as weed population dynamics and the ecophysiological basis of competition will help predict future weed problems and solutions and the economic risks and benefits of intervention. Predictive approaches would help incorporate IWM into models of the processes that occur in agricultural systems at wider spatial and temporal scales, i.e., in agroecosystems comprised of the interactions among organisms (including humans) and the environment. It is at these larger scales that decisions about management are initiated and where questions about the long-term consequences and constraints of IWM and agriculture are often asked. These questions can be addressed by agroecosystem health, an approach that integrates biophysical, social, and economic concerns and recognizes that agriculture is part of a world with many complex subsystems and interactions. Indicators are used to examine the status of an agroecosystem, e.g., whether or not it contains all that is necessary to continue functioning. Indicators include soil quality, crop productivity, and water quality; all of these are related to the rationale of IWM, hence IWM can be linked to agroecosystem health. Ancillary effects of using IWM relate to other indicators such as diversity and energy efficiency. Linking IWM to agroecosystem health has at least two benefits: (1) predictive models within IWM can be incorporated into larger agroecosystem models to explore hitherto unforseen problems or benefits of IWM, and (2) the relevance and benefits of IWM should become clearer to the public and government agencies who otherwise might not examine how IWM promotes many of the larger social, economic and environmental goals being promulgated.**

Additional index words. **Biodiversity, crop productivity, energy efficiency, herbicides, soil quality, tillage, water quality.**

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INTRODUCTION

Weed management is a means to the end of maintaining crop production within a viable agricultural system. There has been a tendency to develop weed management strategies to achieve perceived economic and social goals without linking the strategies to biological factors (40) and without investigating how these different factors interact. A "systems approach" means that weed management and agriculture must be considered as part of the milieu of interactions that may be categorized as social, economic, and environmental (6, 23, 32, 47, 60). Weed management strategies cannot be designed in isolation if they are to be effective and relevant to farmers, extension personnel, industry and, most often neglected (42), government and the public. Integrated weed management (IWM) is a systems approach. IWM incorporates plant breeding, fertilization, rotation, chemical weed control, mechanical weed control, competition, successional management, and soil management into a method of reducing weed interference while maintaining acceptable crop yields (78). It is designed to be economically, environmentally, and socially acceptable. IWM itself is part of conceptual or applied systems at larger spatial and temporal scales, e.g., integrated pest management (IPM), sustainable agriculture, integrated farming systems research/extension, alternative agriculture, best management practices, and agroecosystem health (71, 76, 88). Space limitations force us to examine only agroecosystem health. This term may be unfamiliar but we believe the concept addresses the complexity of agriculturally influenced systems and can be used in communicating abstract concepts effectively.

Agroecosystems describe the interactions among organisms and their environment where agriculture is a primary influence (33, 71). Agroecosystems are complex because of genetic and environmental variation, numerous combinations of interactions (many indirect) in a nested hierarchy of subsystems, and multiple spatial and temporal scales (23, 60, 93). Viewing weed management and agricultural research in the context of nested hierarchies or soft-systems may be the most effective approach as it helps promote a flexible strategy that can anticipate problems and benefits (7). Agroecosystems include humans (70), thus management approaches will be influenced by a diverse set of ideologies and values. "Agroecosystem health" recognizes that humans make decisions about their economic, social, and biophysical environments based on whether or not numerous, occasionally conflicting, criteria are met (88). Often, these decisions are made without explicitly addressing the possible conflicts between these goals or the possible long-term consequences. Given the debate about how health is applicable to (agro)ecosystems (24, 39, 77), its present utility may be that it addresses the human dimension (social, economic, medical) and how humans fit within a world of biophysical limits and processes (88).

Despite the complexity of agroecosystems, tractable and applicable methods of examining agroecosystem health are being developed. One approach is to use indicators to represent the status of various components of agroecosystems (67, 93). For agroecosystem health, indicators should be relevant to specific causes of disturbance, e.g., farm management, and generate testable hypotheses. Indicators can include crop productivity, water quality, soil erosion, pesticide use and losses, energy efficiency, and biological diversity (67). These indicators should be familiar; most of them are related to the rationale for IWM (78).

The goals of IWM and of promoting agroecosystem health are similar in that they seek to minimize adverse environmental and socioeconomic effects. IWM therefore offers a specific approach to improve agroecosystem health. Agroecosystem health relates IWM to large-scale issues, e.g., how IWM will affect energy efficiency of agriculture. Using agroecosystem health offers the means to communicate the benefits and relevance of IWM, especially to those who may view IWM as overly dependent on herbicides (66). Agroecosystem health may help overcome a crucial problem: educating people about what IWM and IPM means (9, 45). If this is accomplished, then it may be possible to use "eco-labelling" of IPM, hence IWM, products. "Eco-labelling" refers to labelling items that are produced using methods that are less harmful to the environment. Agroecosystem health may allow the public to become aware of the benefits of producing food using IWM.

Agroecosystem health is a useful context, but practical implementation of IWM still is a primary goal. While IWM often is supported by government mandates or incentives (15), this does not guarantee acceptance (14). Acceptance and success of IWM will require predictive models of weed-crop dynamics. Eventually packaged as an expert system, models can help assess the short- and long-term economic viability of control measures, assess how various farm management approaches will affect, for example, changes in weed population dynamics. We recognize that this is an ambitious goal and we must first address some of the recent advances in IWM research, successes, shortcomings, and future opportunities. Once this is accomplished, we will return to the issue of how IWM and agroecosystem health are related. To this end, we have developed a conceptual framework relating the general components of IWM (soil and ground cover management, crop and nutrient management, modeling) to agroecosystem health (Figure 1) and a framework of relating the specific components of IWM to five indicators of agroecosystem health (Figure 2).

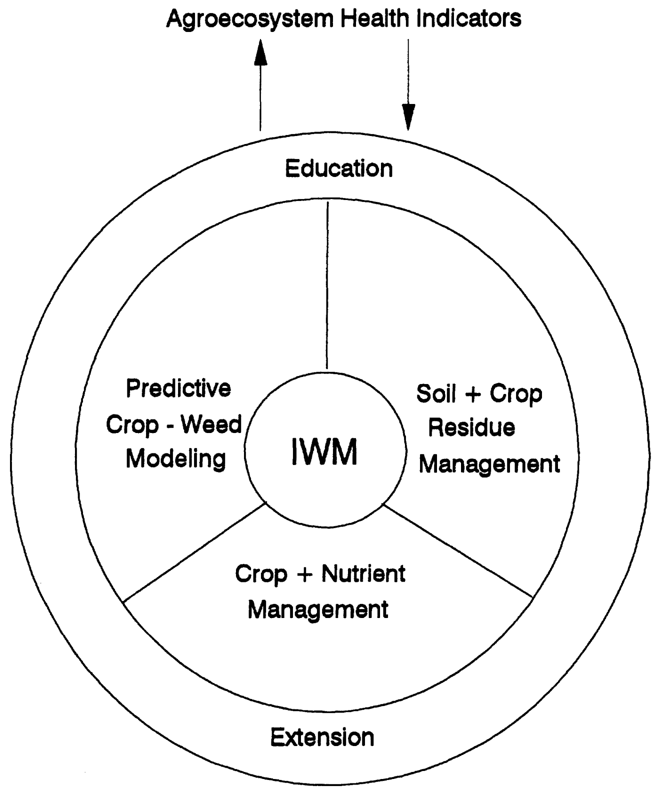

Figure 1. Three general components of IWM as part of the wider context of agroecosystem health.

COMPONENTS OF IWM SOIL AND GROUND COVER MANAGEMENT

Tillage. Conservation tillage is an important component of IWM and is defined as any practice (chisel plowing, ridge tilling, zone-tillage, no-till) that leaves crop residue on at least 30% of the soil surface (78). The benefits of conservation tillage include reduced soil erosion (50), decreased surface runoff of pesticides and fertilizers (34), and maintenance of habitats supporting wildlife and organisms that may regulate agricultural pests (20). Although conservation tillage usually provides the greatest rate of net economic return (97, 98) and lowers costs (91), the willingness of farmers to adopt conservation tillage depends upon their perception of risks and benefits (90, 97, 98).

One concern is whether crop yields decrease under conservation tillage because of increased weed interference. Crop yields under conservation tillage are comparable to those under conventional tillage (15). In the few cases where the yields have not been similar, there have been confounding factors. For example, reduced crop yields may be related to an insufficient workforce to manage no-till fields effectively and lack of appropriate crop rotations (2). Other recent experiments (27, 28) belie predictions that weed population dynamics will change unpredictably such that management will become more difficult, and the weed spectrum will change such that dominant weed species will be those that are perceived to be harder to manage: perennials, grasses, wind-borne species, and volunteers (78, 82). Although there are some case studies where wind-dispersed, perennial, and volunteer weeds were associated with conservation tillage, the trends often have been obscured by the more important variables of location, year, and crop rotation (13, 27). Spatial and temporal variability may reduce the chance that weed problems will necessarily worsen in conservation tillage systems. Such variability

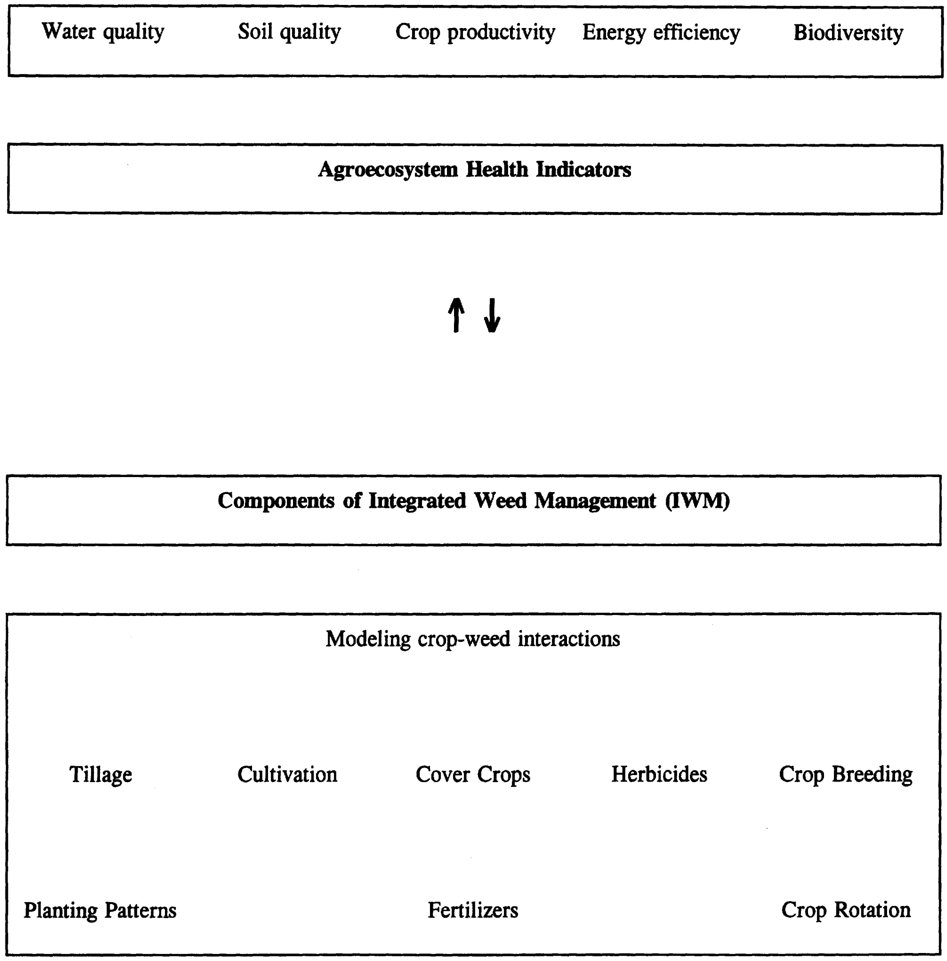

Figure 2. Components of IWM and five indicators of agroecosystem health.

might be viewed as undesirable in that it is more difficult to predict weed problems from year to year in conservation tillage; however, this variability also exists in conventional tillage systems (27). An important conclusion is that benefits of conservation tillage, e.g., reduced erosion, are not offset by adverse changes in the weed spectrum (27, 28). Nonetheless, there is potential for changes in the weed spectrum anytime management changes, e.g., shifting to conservation tillage. As a consequence, weed population dynamics must be monitored and modelled to help predict changes and to develop alternative weed management strategies.

Despite the promotion of IWM as a method of reducing herbicide use (12, 78), there have been concerns that decreased tillage will require increased use of herbicides (66, 78). Predictions of increases in herbicide use assume that the population dynamics of weeds in conservation tillage systems are similar to those in conventional systems and that herbicide technology, and weed management in general, will not change (78). In fact, conservation tillage can affect all aspects of weed population dynamics, e.g., weed seed germination and emergence, intra- and interspecific competition, resource allocation, reproductive effort, seed production, and dispersal (20, 79). For example, crop residue may suppress weeds such that additional herbicide applications are not necessary or provide habitat for weed seed herbivores (20). Generally, these changes may be explained in terms of either shorter-term population fluctuations or longer-term successional changes, and it has been suggested that succession management is a useful extension of IWM as a comprehensive approach to predicting the changes in weed species diversity (20, 79). Succession management requires detailed modeling and weed growth population dynamics; this is an issue to which we will return.

While no-till systems are effective, it has been suggested that tillage still should be a weed management option (30). Modified implements can be used to reduce the intensiveness of soil disturbance (e.g., soil-saver tillage), and the frequency of tillage can be reduced if it is timed to coincide with stages in the weed life cycle when the weed is most vulnerable (78). In modified tillage fields infested with perennial weeds such as quackgrass (*Elytrigia repens* (L.) Nevski), one management option may be using shallow tillage to desiccate rhizomes and alter the method of reproduction to reduce quackgrass' survival and competitive ability (17, 74).

Herbicides. Many countries have policies that mandate the reduction of herbicide and pesticide use and incentives and cooperative programs among government, industry, and farmers (8, 44, 57). Public opinion and government directives to reduce dependence on pesticides require agriculture to respond; IWM can help achieve this. Predictions of increased herbicide use in conservation tillage systems because of the need for preplant treatments (e.g., glyphosate [*N*-(phosphonomethyl)glycine]) or decreased effectiveness have not been supported in most cases (21); however, this needs to be monitored (and modeled) continuously. Of proximate relevance to tillage systems is the development of new postemergence herbicides applied at low rates (g ha^{-1} rather than kg ha^{-1}) (73). These herbicides require well-timed applications to avoid crop damage and minimize weed escapes (74). Appropriate timing is also important with older herbicides and also relates to the need to understand weed and crop growth and population dynamics. For example, glyphosate is especially effective at controlling quackgrass in no-till if it is applied in spring when growth is rapid and translocation of glyphosate is effective (17). The issue of when to apply herbicides is especially relevant to modeling crop-weed interactions (99). As will be discussed in a later section, IWM can promote better timing of herbicide application and decisions regarding whether it is economical to apply herbicides through the use of crop-weed modeling.

Inter-row cultivation. Shallow inter-row cultivation can be used effectively within conservation tillage systems. Inter-row cultivation may be timed to coincide with the time period when weeds are most likely to interfere with the crop (78). To control weeds within the row, herbicides may be sprayed in a band over the row. Banding of herbicides and interrow cultivation reduced herbicide use by 60% in a ridge-till system yet maintained crop yields (30).

Cover crops. Cover crops may be sown into extant crops or the crop residue left after harvest to reduce the time when weeds grow in absence of competition from crops (78, 95). A cover crop's biomass and canopy helps it compete with weeds (69). Autumn-sown cover crops will compete with winter-annual weeds; however, the cover crop dies over the winter and the residue often decomposes before suppression of summer-annual weeds can occur (69). Winter-hardy cover crops compete with summer-annuals but require a quick-acting herbicide, e.g., glyphosate (69). At present, the utility of cover crops is limited. While cover crops and their mulches do not inhibit crop growth in soybean (*Glycine max* (L.) Merr.) or corn (*Zea mays* L.), increase soil moisture (except in dry years), and decrease temperature fluctuations, the large amount of temporal and spatial variability in weed populations has negated any effects on weed germination, emergence, density, and biomass (31, 69). The main advantage of cover crops may be reduced soil erosion and improved soil structure and nutrient cycling (31, 69, 87).

CROP AND NUTRIENT MANAGEMENT

Cultivar competitiveness. Using crop varieties and cultivars that are better competitors with weeds is an important method of weed management (49, 78, 95). Newer corn hybrids are better competitors and are more tolerant of stress, e.g., low nitrogen levels, than older hybrids (84). With more competitive crops, lower dose postemergence herbicides should become more acceptable to farmers. Newer soybean varieties also may be better able to compete with weeds (C. Swanton, unpub. data). Taller and later maturing soybean and white bean (*Phaseolus vulgaris* L.) cultivars promoted early canopy development and increased weed suppression (59, C. Swanton, unpub. data). Although cultivar selection might be influenced by the frequency of tillage to be used, research on white beans has demonstrated that yield depended more on using locally adapted cultivars and disease resistance (75). In general, crops that can germinate, root, emerge, leaf, and grow earlier and faster are more likely to outcompete weeds (78). Further advances in breeding are needed to optimize crop competitive ability because of trade-offs between shoot, root, leaf, and reproductive effort (65).

Planting patterns. Narrower rows and increased crop density can increase crop canopy and the ability of crops to compete with weeds for light and soil nutrients in soybeans and white beans (59, 75, 83, 96, C. Swanton, unpub. data). Despite concerns about increased intraspecific crop competition and disease incidence, yields of corn, soybeans, and white beans in narrower rows either do not change or increase (59, 75, 83, C. Swanton, unpub. data). Often, planting patterns are used with more competitive cultivars, e.g., taller cultivars that are better suited to higher densities (59, 75, C. Swanton, unpub. data). Using narrower rows and increased crop density to reduce weed interference is effective in conservation and conventional tillage systems (75, 83).

Fertilizers. Since addition of nutrients, especially nitrogen, obviates what would be a limiting factor to weed (and crop) growth, weeds have adapted by outcompeting crops for these nutrients and by using nutrients as environmental cues to break seed dormancy (78). To counter these adaptations, nutrients may be placed more precisely, e.g., banded into the crop row or applied using some form of precision technology such as might exist with a global positioning system. These innovations are still in the early stages of development but may have an increasingly important role in IWM. If new cultivars can prosper under lower fertilizer rates yet weeds are adversely affected, then nutrient management and increased crop competitiveness are synergistic approaches (84).

Crop rotation. Crop rotations may reduce pathogenicity, decrease chances of resistance to pesticides, and stabilize nutrient cycling (16, 27, 37). Crop rotations are an important part of IWM and the more diverse the rotation, the easier it is to manage weeds. Nonetheless, one sequence will not necessarily increase or decrease weed interference and alter weed species composition. For example, eliminating fallow in crop rotations but introducing conservation tillage did not change weed species composition (27). Longer-term cropping system studies are needed to examine if differences in crop rotations will affect weed population dynamics in a predictable manner.

MODELING CROP-WEED INTERACTIONS

Predicting when to implement weed control is complicated by genetic and environmental variation (17, 27, 28, 86). Thus, effective models of weed morphological development, population dynamics, crop-weed competition, and the economics of weed management measures under varying conditions are needed. Modeling attempts to combine many factors to determine if control measures will be needed in the short- and long-term (54, 78, 95). It addresses an important challenge for weed science: a shift from descriptive to predictive approaches. Before such models become practical, however, there are several aspects that need to be explored in detail.

Weed seed germination and seedling emergence. The time of weed seed germination and seedling emergence, relative to the crop, influences crop yield loss from weed competition (19, 55, 56). Practical implementation of critical periods and weed economic thresholds require the ability to predict when weeds will emerge (29, 62). Predictions of germination and emergence are confounded by genetic, climatic, and management-induced environmental variation, especially in terms of soil moisture and temperature and their interaction (68, 89). Germination and emergence models are being developed for several weed species in different tillage systems in our laboratory and elsewhere (35).

Critical periods of weed control. Predicting the timing of weed emergence relative to the crop will help determine the critical period of weed control, i.e., the time interval when it is essential to maintain a weed-free environment to prevent yield loss (43, 78). The critical period of weed control consists of two subunits: (a) the critical weed-free period—maximum length of time weeds emerging with a crop can be allowed to grow until they begin to cause unacceptable yield losses, and (b) the critical weed removal period—minimum length of time weeds that emerge after a crop must be removed so that unacceptable yield losses do not occur (43, 85, 94). Critical periods can be used to determine when farmers should apply herbicides. To account for environmental variation, critical periods are defined relative to the crop growth stage (85). Even with this proviso, the spatial and temporal variation may be so large that critical periods need to be defined for specific crop-weed-site-year locations (43). Predictive models are not yet feasible and probably will not be until weed germination and emergence can be predicted. In general, critical periods in white beans, corn, and soybeans are relatively short if the acceptable yield loss is defined as 5% (43, 85, 94). This means that the biological and economic value of applying herbicides is low except within a very narrow time period (85). Thus, season-long residual herbicides may not be needed and nonresidual postemergence herbicides may be timed effectively to reduce cost and amount of herbicide (43).

Weed economic thresholds. Just as models of weed germination and emergence are related to critical period models, so too are critical period models related to weed economic threshold models (51, 52). In theory, growers should apply additional herbicides to escaped weeds during the critical period if an economic threshold has been reached, i.e., if the yield loss avoided is greater than the cost of application (22, 43, 85, 89, 92, 94). Critical period models indicate when herbicides are needed; weed economic threshold models determine if weed density and, concomitantly, interference, is sufficient to justify control measures during the critical period. Weed economic threshold models predict the relative competitive ability of weeds based on time of emergence and density; this can determine if weed control measures will be cost-effective (89).

Weed economic threshold models may be based on empirical weed-crop competition models, i.e., predict yield loss as a function of relative weed leaf areas. Relative leaf area (RLA) accounts for weed emergence and density, hence it is a better representation of weed competitive ability; for extension purposes, RLA would allow farmers to base predictions on a single time of assessment (18, 19, 52, 54). The weed-crop competition models have indicated that later-emerging weeds may not require control because they cause little crop yield loss (19, 29, 51). As with critical periods, the models presently are limited to a specific combination of one of each of a crop species, weed species, year, and location; however, incorporating the relative growth rate of the weeds and the crop has reduced some of the year and site variation (18, 52). As a result, we have been able to construct one weed economic threshold model for decisions on use of postemergence herbicides (29); however, it still requires more accurate predictions of (a) crop price, yield, growth rate, competitive ability, (b) weed spatial distribution, density, competitive ability, and (c) the overall influence of farm management practices (29).

The inability of empirical competition models to account for year and location variation (18, 19, 29, 51, 81) means that ecophysiological models may be more useful. Ecophysiological models are based on limits to physiological processes, e.g., those affecting morphological development and nutrient uptake (55, 56, 63, 64). Ultimately, these models may predict how emergence date, density, photoperiod, and temperature affect morphological development and allocation of resources between reproduction and vegetative growth in response to competition (63, 64, 65). Ecophysiological models also may help explain why critical periods exist, predict when they might occur, and offer a cost-effective strategy. For example, competition for light between weeds and either soybean or white bean is the crucial factor in determining yield loss during the critical period (86, 94). A crop may outcompete weeds for light if one uses narrower row widths or cultivars that emerge and branch earlier (86).

Weed population dynamics. Modeling weed population dynamics is an elusive goal but it is crucial to predicting future weed problems, including herbicide resistance, as well as more general effects of weed and agricultural management on agroecosystems (48, 57, 61, 62). For example, predicting changes in seedbanks with management (tillage, herbicides) will help predict changes in species composition, adjust weed management strategies to new tillage practices, and facilitate adoption of conservation tillage and reduced herbicide use (3, 4, 10, 36, 46, 78, 79). IWM may promote increased populations of organisms that will consume or infect weeds and their seeds and perhaps increase intraspecific competition and competition between weeds because of changes throughout the weed life cycle (5, 20, 53).

IWM WITHIN THE CONTEXT OF INDICATORS OF AGROECOSYSTEM HEALTH

One of the challenges for IWM is promoting it as a viable component of a cropping system to farmers, extension personnel, government, and the public. Agriculture is becoming better integrated into larger fields of research and is combining with fields as diverse as economics, ecology, sociology, landscape planning, political science, engineering, and philosophy. The public, government, industry, and growers must be offered ways of cooperating to promote rather than mandate IWM. Ontario's success in cooperative efforts to reduce pesticide use is one good example (44). Systems approaches, such as agroecosystem health, offer ways of structuring agricultural research to help ensure that diverse interests are represented. Integrated weed management already embraces many of the same goals and approaches as agroecosystem health; what has been lacking are explicit examples of how IWM relates to wider-scale approaches to agroecosystem health.

Five indicators of agroecosystem health. Despite problems of interpretations that can differ with spatial or temporal scale (60, 93), there are broad indicators that can be used to describe whether or not an agroecosystem is functioning at acceptable environmental, economic, and social levels and whether or not it will continue to function acceptably. Crop productivity, water quality, soil quality, energy efficiency, and biological diversity are some of the indicators available to examine agroecosystem health (67). We chose these five because they are relevant to IWM (Figure 2); our list is neither exhaustive or exclusive (e.g., 23, 60, 93). These indicators are not necessarily independent of one another and cannot be used to compute an aggregate index of health. They are indicators that can be used to form a series of hypotheses about agroecosystems. These five indicators are relevant to the structure and function of agroecosystems and the implications of IWM. In all cases, the role of crop-weed modeling is important as it predicts the response of the general indicators of agroecosystem health to the specific components of IWM and, as models become more sophisticated, interactions between these components.

Crop productivity and energy efficiency. In IWM, improving or maintaining crop production is important. Improvement may result if conservation tillage improves soil quality and associated nutrient cycling, crops are more competitive with weeds and disease-resistant, and nutrient and herbicide applications are better timed and better placed. Crop productivity can be linked to energy efficiency. Energy efficiency expresses how much output (crop production per unit of land) is derived from external inputs (herbicides, fertilizers, seed). Contrary to popular assumption, agriculture is becoming more energy efficient (21). Any system that is less reliant on external inputs, as represented by energy, is likely to be more self-sustaining and healthier (23, 58, 60). Some of this is attributable to IWM because it reduces inputs by using the approaches detailed in our discussion of soil and ground cover management, crop and nutrient management, and modeling crop-weed interactions (20, 21). If the models of crop-weed competition and weed economic thresholds become useful in the next decade, energy efficiency will improve because better-timed applications of inputs will decrease energy use.

Soil and water quality. As indicators, soil and water quality collectively express such characteristics as soil porosity, bulk density, organic matter content, and oxygen content. They are attractive indicators but their response to IWM will vary with physiographic factors such as soil parent material and slope. In general, however, increased crop residue and decreased tillage reduce soil erosion and decrease surface runoff of pesticides and nutrients (78); conservation tillage may increase porosity such that ground water contamination can increase but the evidence is equivocal (34). As yet, it has not been determined how effective crop-weed modeling and more timely intervention will be at reducing erosion and contamination but we predict it will be important. There may be increased efficiency in nutrient cycling with greater numbers and diversity of interacting organisms (20).

Biodiversity. Biological diversity (biodiversity) may be familiar to the public; hence, it is useful as an indicator as long as it is applicable to agriculture. Biological diversity responds to changes in agricultural management (26, 38, 67, 72, 93). Using conservation tillage, cover crops, crop rotations, reduced pesticides, and more competitive, locally adapted cultivars should increase biodiversity, especially in terms of the number of species that act as herbivores, predators, detritivores, and decomposers (20). Increases in biodiversity may increase nutrient cycling, interactions with marginal and off-farm organisms (e.g., pollinators), and self-regulation of populations, especially pests (1, 20, 25, 79, 80). If increased self-regulation occurs, an agroecosystem may be more self-sustaining; however, we emphasize that this is a hypothesis that has to be tested extensively (80). Predictive models related to biodiversity are needed to determine benefits in terms of conservation and self-regulation and risks in terms of pest management (20). The effect of IWM on the wider issues of habitat and landscape diversity also may become important in terms of agroecosystem health at larger spatial scales and in terms of soil and water quality.

THE FUTURE OF IWM

If IWM is to continue to be successful in the coming decades, it must be able to adjust to environmental, economic, and social changes. IWM must be more than a mandated program advocated only by research scientists and government policy analysts. It must be part of a larger systems approach that includes environmental, economic, and social concerns that have not been traditionally part of agricultural research but to which agriculture has relevance. IWM must be explained in terms of agroecosystems, and the benefits and limitations must be addressed explicitly so people from across the sociopolitical spectrum (environmental activists, ranchers, farmers, urbanites) can make informed decisions. There may be unease with the agroecosystem health approach because of its unfamiliarity and early stages of development as a concept. We believe that agroecosystem health is a useful communication tool that can help educate people about why IWM is an important part of agriculture's future. The task of implementing IWM within agroecosystem approaches is daunting. Nonetheless, progress has been made and IWM is beginning to move from the conceptual to the applied phase. Though technological improvements in herbicide chemistry, genetic engineering of crops, and application systems such as global positioning systems will be important components of IWM, technology alone cannot obviate biophysical limits indefinitely (11, 41). Technological advances need to be considered in our approach to examining and managing agroecosystems.

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