Integrated Pest Management of Insects, Plant Pathogens, and Weeds in Dryland Cropping Systems of the Great Plains

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In this article, we trace the development of the concepts and practices of Integrated Pest Management (IPM). Tactics used in IPM of insect pests, plant pathogens, and weeds are discussed, with particular emphasis on application to dryland cropping systems of the Great Plains. Recommendations are made for guiding the development of IPM in such systems.

THE ORIGINS of the theory and practice of IPM can be traced to the last century within the disciplines of applied ecology, entomology, plant pathology, weed science, horticulture, and soil and crop sciences. The term IPM evolved in the late 1960s from its antecedent terms, Integrated Control and Pest Management, which had been introduced in the 1950s. The rapid development of the concepts and practices of IPM in the 1950s occurred in response to the problems created by the use of synthetic organic insecticides following World War II. The term is now used routinely in relation to the management of insect pests, plant pathogens, and weeds (Cook, 1994; Thill et al., 1991).

Despite the relatively long history of IPM (recently reviewed by Cate and Hinkle, 1993), definitions and descriptions still vary widely. We will use a description of IPM modified slightly from Cate and Hinkle (1993).

> IPM is the judicious use and integration of various pest control tactics, in the context of the associated environment of the pests, in ways that complement and facilitate biological control and other ecological processes that reduce pest impact, to meet economic and environmental goals. IPM addresses the basic causes of pest problems in a holistic manner.

This description recognizes that a pest is a component of an agroecosystem and an agricultural landscape; it also recognizes that management actions may have impacts on many aspects of the system. Further, this description recognizes that successful IPM is critically dependent on understanding the biology and ecology of pests and their various roles in agroecosystems. In addition, this description uses terminology appropriate to management of all three major groups of organisms commonly considered pests in agriculture: arthropod pests, weeds, and plant pathogens.

IPM TACTICS

The most important management tactics used in IPM can be grouped within four major categories: (i) pesticides, (ii) host plant resistance, (iii) biological control, and (iv) cultural practices. Table 1 lists subcategories within each of the major groups.

Although they use somewhat differing classification schemes and terminology, Baker and Cook (1982), Burn et al. (1987), Cate (1990), Cook and Baker (1983), Dent (1991), Horn (1988), and Pedigo (1989), provide discussions of many of the tactics listed in Table 1.

IPM: A DECISIONMAKING PROCESS

At its core, IPM is a problem solving, decisionmaking process. The process leads to decisions regarding what tactics to use and when and how to use them. These decisions are strongly influenced by the spatial and temporal scales that characterize agricultural landscapes and pest problems (Landis, 1994).

Use-Patterns of Management Tactics

In this framework, three general (somewhat overlapping) use-patterns for management tactics can be recognized (Table 2): (i) tactics can be incorporated into the design of the cropping system to reduce the likelihood of a pest problem developing over a large spatial and temporal scale; (ii) tactics can be applied in anticipation of a problem if the problem seems likely to develop in the near future (for example, the current growing season), at a relatively small spatial scale (for example, a specific field); and (iii) tactics can be applied to reduce the impact of an active problem that has already developed in a specific place (for example, a field or part of a field). Table 2 categorizes tactics listed in Table 1, according to their use-patterns in IPM systems.

In Table 2, pesticides are rated as generally used against active pest problems. Pesticides also are used effectively in some situations when a problem seems likely to develop in the near future. For example, fungicides are often applied to protect crops from anticipated disease outbreaks, and herbicides can be applied to prevent weed–crop competition later in the current cropping season or to prevent weed seed production that would affect crops planted later. However, pesticides generally are not tactics that are designed into a cropping system. A possible exception is herbicides used in some reduced tillage systems. For example, in the Great Plains, no-till fallow cropping systems are considered highly desirable because they increase water storage in the soil and thus enhance cropping options. In addition, reduced tillage conserves soil organic matter and reduces erosion from wind and water. In such systems residual, broad-spectrum herbicides are applied routinely following harvest to

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Abbreviations: BCA, biological control agent; EIL, economic injury level; HPR, host plant resistance; GPS, global positioning system; IPM, integrated pest management; RWA, Russian wheat aphid; WSMV, wheat streak mosaic virus; WSS, wheat stem sawfly.

Table 1. IPM Tactics.

Pesticides
Chemical
Biological
Host plant resistance
Biological control†
Importation and release
Conservation
Augmentation
Cultural practices
Rotations
Interplantings
Cover crops
Planting density
Pest-free planting materials
Planting date
Harvesting date
Tillage
Sanitation
Field size
Adjacent land uses
Soil fertility management
Irrigation management

† The sub-categories under Biological Control are commonly used in reference to pest insects and weeds, but are not commonly used in relation to plant pathogens.

Table 2. Use-patterns† for IPM tactics.

Tactic	Incorporated into cropping system design	Applied for near-term future problem	Applied for currently active problem
Pesticides	+	++	++++
Host plant resistance	++++	++	0
Biological control			
Importation and release	++++	0	0
Conservation	++++	++	0
Augmentation	0	+	++++
Cultural practices			
Rotations	++++	+++	0
Interplantings	++++	++	+
Cover crops	++++	++	+
Planting density	++++	+++	0
Pest-free planting materials	++++	+++	0
Planting date	++++	++	+
Harvesting date	++++	++	++
Tillage	++++	+++	+++
Sanitation	++++	++	+
Field size	++++	+	0
Adjacent land use	++++	+	+
Soil fertility management	++++	++	+
Irrigation management	++++	++	++

† A rating of 0 indicates the tactic generally is not used in the stated way in IPM systems. A rating of + or ++ indicates the tactic sometimes is used in the stated way; and a rating of +++ or ++++ indicates the tactic generally is used in the stated way.

control weeds that would otherwise emerge at various times over the fallow period.

Host Plant Resistance (HPR) is most often used by incorporating cultivars resistant to the pest into cropping system design. In some situations, however, a farmer might decide to plant a resistant cultivar only if there is evidence that a pest problem is likely to develop during the cropping year. This strategy is especially reasonable if the resistant cultivar has a lower yield potential (in the absence of the pest) or lower quality than an alternative cultivar.

Biological control in this classification refers to the effects of biological control agents (BCAs) on pests. Entomologists typically use the terms predator, parasitoid, and pathogen to refer to the various BCAs of insect pests. Entomologists and weed scientists typically use the terms herbivore, seed predator, and pathogen to refer to BCAs of weeds. Plant pathologists typically refer to BCAs of plant pathogens as antagonists.

The three major categories of biological control typically recognized by entomologists (Cate, 1990) differ greatly in use-pattern. The importation and release of BCAs, often called "classical biological control" by entomologists, typically is aimed at the management of a pest that has been accidentally introduced from another continent [such as leafy spurge (*Euphorbia esula* L.), Russian knapweed [*Acroptilon repens* (L.) DC], Klamath weed (*Hypericum perforatum* L.), European corn borer (*Ostrinia nubilalis* Hubner), greenbug (*Schizaphis graminum* Rondani), Russian wheat aphid (*Diuraphis noxia* Mordvilko), corn leaf aphid (*Rhopalosiphum maidis* Fitch), and Hessian fly (*Mayetiola destructor* Say). The native range of the pest is explored for BCAs that are likely to reduce the impact of the pest in its new environment. The BCAs are then imported and released in the agroecosystem and become permanently established. Thus, they become part of the cropping system design. The record of success for this type of biological control is not very encouraging in highly unstable environments such as annual cropping systems. However, the relative lack of success may be in part the result of our poor understanding of the attributes of BCAs that are essential to success in such environments (Gilstrap, 1996).

Biological control through conservation is usually achieved through habitat modifications that favor or enhance existing BCAs (either native or introduced) and reduced use of pesticides that disrupt biological control. Like importation and release, conservation can be built into a cropping system; but actions to conserve BCAs also can be applied if a pest problem is anticipated later during the cropping year.

The most common form of augmentation (or periodic release of BCAs) is the release of overwhelming numbers of BCAs to reduce a pest problem that is active or anticipated (often referred to as inundative release). Although this tactic is used effectively in some cropping systems, justifying its expense is difficult in most dryland situations.

Cultural practices generally are most effective if designed into the cropping system. However, some can be applied to problems that are anticipated (for example, rotation out of corn [*Zea mays* L.] to another crop, if a corn rootworm [*Diabrotica* spp.] problem is anticipated). In addition, certain cultural practices can be applied to pest problems that have already developed. Examples include tillage for weeds and altering the harvesting date of alfalfa (*Medicago sativa* L.) for alfalfa weevil [Hypera postica (Gyllenhal)].

Economic Injury Level and Sampling

The concept of the economic injury level (EIL) was developed as a decision tool in the 1950s by entomologists who were trying to promote use of insecticides only in those situations where biological control, HPR, cultural practices, or other ecological processes had failed to keep the pest population below a tolerable level. The concept recognizes that pest densities, up to some level, can be tolerated and that insecticide application is not justified if that density is not exceeded. Obviously, the use of EIL was initially conceived to apply to decisions concerning active insect pest problems (Table 2).

Using the EIL concept, the decision to apply a tactic (usually a pesticide) is justified only if the benefit is greater than the cost. In a simple form, this cost-benefit analysis considers: the cost of applying the tactic, the value of the crop, and crop yield loss (or quality loss) associated with various levels of the pest (more detailed consideration of the EIL can be found in Coble and Mortensen, 1992; Funderburk and Higley, 1994; Funderburk et al., 1993; Pedigo et al., 1986, and references therein). Additional factors also have been recognized as being important in the decision process. Weed scientists have explicitly factored in the cost of the increase in the weed seed bank that will occur if the current weed problem is not dealt with effectively (Bauer and Mortensen, 1992; Cousens, 1987; Swinton et al., 1994). Entomologists have considered the effects of insecticides on BCAs and have attempted to use BCA abundance in the decision process (Croft, 1990; Nyrop and van der Werf, 1994; Wilson, 1985). The relationship between EILs and environmental concerns has been discussed by Higley and Pedigo (1993), and Higley and Wintersteen (1992) have attempted to account explicitly for costs associated with environmental risks related to pesticide use.

The development of EILs for use in the decision process requires a wide variety of high quality information (biological, agronomic, economic, and environmental). Critically important is information on the yield-loss relationship for the pest under a variety of conditions. A somewhat oversimplified description of the yield-loss relationship (specifically for insects) is: the amount of yield or quality loss per pest per day, for plants at various growth stages, and under various other stresses. This complex relationship can be greatly influenced by cultivar, growing site, and other situation specific characteristics. Thus, the detailed, reliable information necessary to develop precise EILs can only be obtained through painstaking research and years of field experience.

Once EILs are established, high quality information on the current status of pests and other factors must be obtained in the field. Essential information includes: the status of the crop (How mature is it? What is its yield potential? How vulnerable is it to pests?), the status of naturally occurring BCAs (What is their likely impact?), and the status of other factors—such as soil moisture, soil fertility, crop residue, etc. (What is their likely impact on pests and the damage the pests may cause?) Typically, this information is obtained by field scouts who monitor the crop on a regular basis.

As a result of the information needs associated with establishing EILs, over the last 35 years entomologists (and more recently, weed scientists, and plant pathologists) have placed very high emphasis on accumulating yield-loss data for many pests. Great emphasis also has been placed on developing effective and efficient sampling schemes for use by field scouts who are monitoring crops (Pedigo and Buntin, 1994). Elliott et al. (1994) reviewed sampling of arthropod pests of wheat (*Triticum aestivum* L.)

Despite the progress that has been made, lack of information on the complex relationship between pests and yield loss and on sampling methods is still regarded as an important emphasis for future research in many pest systems.

Limits to the Usefulness of the EIL and Sampling

Monitoring and the EIL concept have been enormously important to IPM of arthropods in many crops, and there are many promising developments in the use of EILs in IPM of weeds (Coble and Mortensen, 1992; Schweizer et al., 1994). Monitoring methods and EILs also have been developed for certain specific plant diseases in some cropping systems. For example, in irrigated beans in eastern Colorado, a management program based on monitoring for rust spores on foliage has been developed. Spore (pustule) densities, together with macroenvironmental data, stage of crop development, varietal susceptibility, and other information from the field, are used to make predictions about disease development and the cost effectiveness of fungicide treatments (Schwartz and Brick, 1993).

However, despite the many examples of the applicability and importance of EILs and monitoring in IPM, they generally seem to be much less central to the IPM of plant pathogens (Schumann, 1991); and they may be much less useful in the dryland cropping systems of the Great Plains than in many other cropping systems for the IPM of all pests—including arthropods. A number of factors play a role in limiting the usefulness of the EIL and monitoring in IPM.

The applicability of EILs and sampling to IPM of plant pathogens is limited in part by the lack of effective pesticides for many plant diseases. Thus, the opportunities to reduce an active pest problem are more limited for plant pathogens than for arthropods (Schumann, 1991). If tactics are not available to reduce an active pest problem, the concept of EIL, as it is commonly understood, is not applicable. Even for those plant diseases for which there are effective pesticides, the appearance of symptoms and the occurrence of damage may be mechanistically very closely associated (Schumann, 1991). Typically, pathogen population densities cannot be easily or efficiently quantified and linked to predictions of economic damage from disease in ways analogous to those used to link insect densities to predictions of economic damage. Thus, basing treatment decisions on sampling and an EIL may not be possible for many plant pathogens.

From a cropping systems view, by far the most important factor limiting the usefulness of the EIL and sampling in dryland systems is the relatively low value of the crops. The expense associated with gathering information about the status of pests and the crop (sampling or monitoring) makes the routine use of this practice questionable. This is in sharp contrast with higher value crops (such as citrus (*Citrus* spp.), cotton (*Gossypium hirsutum* L.), tobacco (*Nicotiana tabacum* L.), tomatoes (*Lycopersicon esculentum* Miller), and soybeans [*Glycine max* (L.) Merr.] where the concepts and practices related to the EIL were developed. In addition, even if a problem is detected and is deemed to be above the EIL, the cost of applying an additional pesticide probably will be a severe threat to the grower's profit potential. In dryland systems, farmers simply cannot afford to deal with very many pest problems once the problem is in progress.

IPM IN DRYLAND SYSTEMS

Because of the expense of monitoring pests and other conditions in the field and of applying the tactics that are best suited for dealing with active pest problems (pesticides and augmentative biological control), the major focus of IPM development efforts for dryland systems clearly should be on other tactics. In addition, the need for environmentally sound IPM also makes development of other tactics desirable. Thus, to meet the challenges of developing and implementing workable, economically feasible, environmentally acceptable IPM in the dryland systems of the future, we would place primary emphasis on tactics that can be designed into the cropping system. We would place secondary emphasis on some of the tactics that can be applied in anticipation of a pest problem during the current cropping year.

Economic Injury Levels and Monitoring in Dryland Systems

Despite the usual emphasis given to EILs and monitoring in IPM, we would place relatively low emphasis on developing and refining these tools for use in dryland systems. This is because EILs are most readily applied to the decisionmaking process related to pest problems in progress. In addition, there is less need for precisely defined EILs because growers cannot afford to acquire enough information from their fields to make effective use of more refined EILs. However, monitoring for pest problems in dryland systems may become more feasible through technological advances. For example, remote sensing has potential to greatly reduce the cost of acquiring pest information in dryland systems. Thus, we would encourage investments in developing technology that will enhance the remote sensing of pests, the environments where pests are likely to reach damaging levels, the effects of pests on crops, and so forth. The Global Positioning System (GPS) is another technology with potential applicability for IPM in dryland systems. This technology has received a good deal of attention in relation to site-specific nutrient management (Reetz, 1994) and also is being explored as a weed management tool (B.D. Maxwell and G.A. Nielsen, 1995, personal communication). Using GPS units mounted on harvesting equipment, producers may be able to gather precise spatial information on weed occurrence during harvest. From these data, maps can be developed showing the exact location of weed problems. With a GPS unit mounted on herbicide application equipment, a producer could navigate to areas with severe weed problems and treat them. Because of the predictable dispersal characteristics of many weeds, such weed maps may be reliable for several years, thus further improving the potential cost-effectiveness of this approach.

Tactics for Dryland Systems

Host plant resistance, importation and release of BCAs, conservation of BCAs, and certain cultural practices are especially suited to being designed into cropping systems or to being applied in anticipation of a pest problem during the current cropping year. In this section we will focus in more detail on the use of HPR, crop rotation, and planting dates in dryland systems.

Host Plant Resistance

Pest resistant cultivars have many advantages as an IPM tactic. They are inexpensive to deploy once they are developed, and they are generally safe to the environment. On the other hand, there is cause for human health concern regarding the introduction or enhancement of some types of resistance factors (Eigenbrode and Trumble, 1994); resistant cultivars may be costly to develop; and the process may take many years. Both the cost and the time required for their development are made much greater if the effort is expanded to include combining resistance to multiple pests into a single cultivar. At present, screening typically requires exposing various lines to live pests. Thus, screening simultaneously for many pests requires a major commitment of resources. In addition, once genes for resistance to multiple pests are identified, there are formidable challenges to developing a single cultivar containing all the genes for resistance (Heinrichs, 1994). Developments in molecular tagging of resistance genes has great potential to facilitate this process. Although HPR is sometimes quite long lasting, it can be overcome through genetic changes in the pest (Gould, 1991; Hatchett and Gallun, 1970; Puterka and Burton, 1990; Shufran et al., 1992).

Host plant resistance has been mainly emphasized as a tactic for arthropods and plant pathogens, but it has been applied to weeds as well. Resistance to damage from weeds is mainly related to breeding for more competitive plants. Crop competition with weeds is generally greater if crop plants are taller and have more rapid canopy development (Callaway, 1992). However, there are important interactions with cultural practices. Figure 1 (from Anderson, 1994b) shows an example of the reduction of weed seed production in both volunteer rye (*Secale cereale* L.) and jointed goatgrass (*Aegilops cylindrica* Host.). A small reduction in weed seed production was achieved by placing N fertilizer away

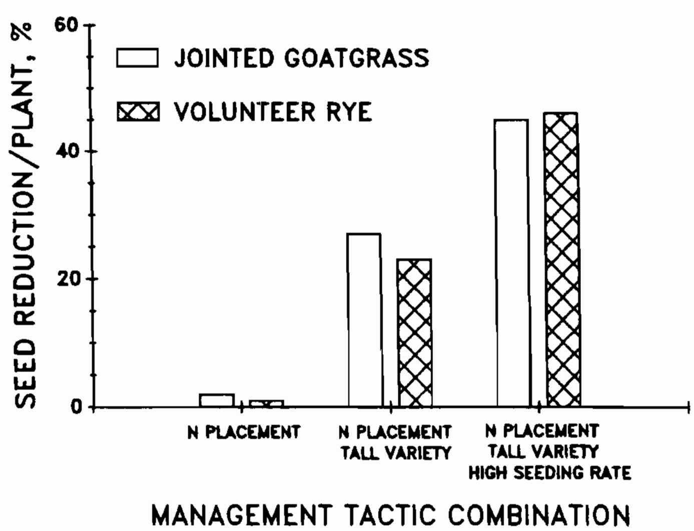

Fig. 1. Effect of combining cultural practices on seed production/plant of jointed goatgrass and volunteer rye growing in winter wheat (Anderson, 1994b).

from weeds. Seed production was reduced much more when N placement was combined with planting a taller, more competitive wheat cultivar. Seed production was reduced still further if the seeding rate also was increased. This combination of a competitive cultivar with other cultural practices in winter wheat also reduces summer annual grass populations in future crops such as corn and sorghum [*Sorghum bicolor* (L.)Moench] because of its impact on in-wheat weed seed production (Wicks et al., 1986).

Producers also may be able to reduce herbicide rates by using competitive cultivars in conjunction with cultural practices that enhance the crop's competitiveness. With barley (*Hordeum vulgare* L.), increasing seeding rate of a tall variety planted in narrow rows enabled several herbicides to control wild oat (*Avena fatua* L.) at half the normal use rate (Barton et al., 1992).

Crop Rotations

Changes in the crop rotation can have very profound impacts on a cropping system, on the agroecosystem, and on the agricultural landscape. While the impact rotations have on the system can be favorably exploited, some negative impacts of such major changes in the cropping system also are likely.

Crop rotation is an important tactic for management of winter annual weeds in fall planted wheat. Winter annual weeds (volunteer rye, jointed goatgrass, and downy brome [*Bromus tectorum* L.]) have life cycles that are similar to winter wheat; and thus, they tend to be favored by the conditions that favor wheat. Anderson (1994b) has documented the proliferation of winter annual grasses in a winter wheat-fallow system in the Central Great Plains. Fields infested with these weeds have a reservoir of weed seed in the soil. This assures that future crops also will be infested with these weeds. Figure 2 (from Anderson, 1994b) shows weed seed survival in soil over time. Less than 80% of volunteer rye or downy brome seed is viable after 1 yr in the soil. Jointed goatgrass seed persists longer, with approximately 20% still viable after 2 yr. Depletion of the seed bank over time (Karssen, 1982) results from germination, microbial and insect predation, and other natural mortality factors. Adding summer annual crops to the rotation, such as winter wheat–corn–fallow, lengthens the time before the next wheat crop—thus reducing the winter annual weed problem. Enhancing the mortality of weed seeds in the seed bank may be an important area for future efforts in biological control of weeds.

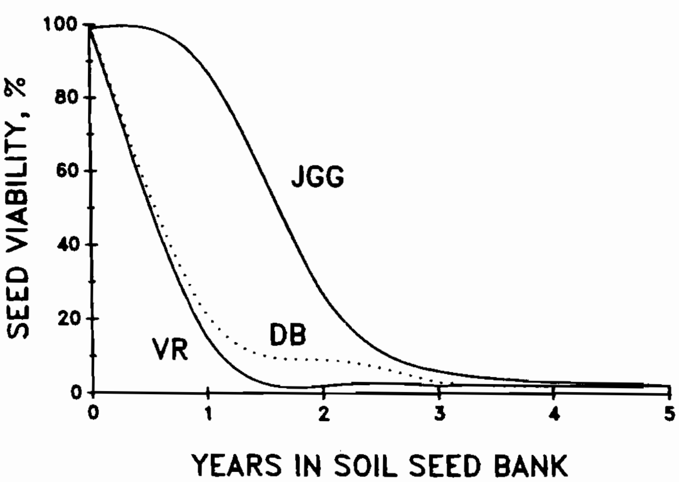

Fig. 2. Length of survival of volunteer rye (VR), jointed goatgrass (JGG), and downy brome (DB) seeds in soil (Anderson, 1994b).

Crop rotation can also be used as a management tactic against summer annual grasses associated with corn in the Central Great Plains. These weeds include green foxtail [*Setaria viridis* (L.)Beauv.], longspine sandbur [*Cenchrus longispinus* (Hack.) Fern.], and wild proso millet (*Panicum miliaceum* L.) (Wicks and Smika, 1990). All of these species germinate in May and produce seed by late August, thus completing their life cycle within the growing season of corn. This weed-crop synchrony in life cycle can be disrupted by rotating to winter wheat. Thus, the weed seed bank of both summer and winter annual weeds can be depleted in rotations of summer and winter annual crops such as corn and wheat (Anderson, 1994b; Burnside et al., 1981).

Another option is to rotate plant class, that is, a grass crop with a broadleaf crop. Changing plant class provides producers with different herbicide options to control selected species. For example, planting sunflower (*Helianthus annuus* L.) after corn allows the producer to apply herbicides for control of grasses—herbicides that would injure corn. However, if a producer planted another grass crop, such as proso millet, summer annual grass populations would increase because proso millet's life cycle is similar to corn and herbicide selectivity for weed control is similar for both crops.

Tan spot, caused by *Pyrenophora tritici-repentis* (Died.) Drechs., and leaf blotch, caused by *Septoria tritici* Roberge in Desmaz., are examples of major plant pathogens of wheat in dryland systems that are very favorably managed through rotations that include winter wheat–corn (or grain sorghum)–fallow (Bockus and Claassen, 1992; Doupnik and Boosalis, 1980). Rotation to other crops is effective because the inoculum tends to carry over to the next crop on the plant residue, and rotations extend the time during which mortality factors can reduce the inoculum level. In addition to the direct effects of these rotations on diseases, Doupnik and Boosalis (1980) also reported a decrease in the incidence of stalk rots in sorghum in their reduced tillage rotations. The decrease in stalk rots was attributed to lower soil temperatures in sorghum, resulting from the effect of wheat residue and to the reduction of moisture stress in the sorghum, again attributable to the wheat residue.

Unfortunately, the effectiveness of crop rotation (like most other tactics) can be overcome through resistance mechanisms in the pest. For example, corn rootworm eggs are laid in the soil around corn plants in late summer. If corn is planted in the same place the following year, newly hatched rootworms will easily find corn roots to eat. If instead, a non-corn crop is planted, the larvae will die because they cannot find appropriate food. However, resistance to rotation has been reported (Krysan et al., 1986). The mechanism at work for northern corn rootworms (*D. barberi* Smith and Lawrence), is that some eggs now remain dormant for two years (or longer) and thus emerge when corn is planted the next time. Another mechanism has recently been proposed as an explanation for western corn rootworm

(*D. virgifera virgifera* LeConte) damage to corn following soybeans. In this case, the rootworm adults are suspected of having changed their oviposition behavior so that they now lay eggs at the base of soybean plants. If corn is planted at that site the next spring, corn roots will be readily available for the newly hatching larvae (Levine, 1995).

Planting Date

Another important factor that can be employed as an IPM tactic is planting date. For example, planting proso millet on 1 June rather than 15 May reduced kochia [*Kochia scoparia* (L.) Schrader] population by 60%, yet grain yields were not affected (Anderson, 1988).

Weed problems also can be managed by choosing crops with different preferred planting dates. Longspine sandbur emerges in late May and June and flowers in late July. The seed is enclosed within a bur, which lessens the value of contaminated hay. Hay from foxtail millet [*Setaria italica* (L.)Beauv.] which is planted in early June and harvested for hay in late August (Lyon and Anderson, 1993), will be contaminated with burs if longspine sandbur is present. Oat (*Avena sativa* L.), another option for hay, is planted in early April and harvested in late June. Thus, growing oat would result in hay harvest before longspine sandbur develops burs, consequently preventing bur-infested hay.

Shown in Fig. 3 (from Anderson, 1994a) is the seedling emergence pattern for a weed community. This information could be employed in the decision of what oil seed crop to plant. In the Great Plains the two commonly grown oil seed crops are safflower (*Carthamus tinctoris* L.) and sunflower. Safflower is planted in early April while sunflower is planted in early June. Potential number of weeds emerging in each crop contrasts drastically. With safflower, over 70% of total weed seedlings would emerge within 10 wk after planting. However, if sunflower were planted after 13 June, over 80% of weed seedlings would have emerged before planting. These weeds could easily be controlled with either tillage or herbicides.

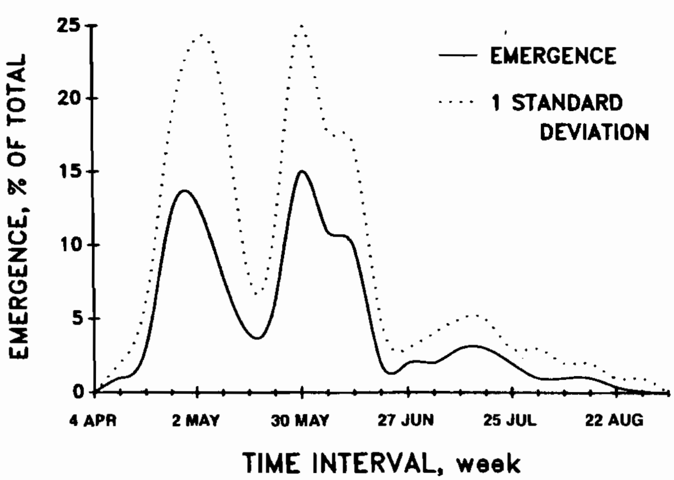

Fig. 3. Weed community emergence pattern (solid line) average over 7 yr. Dotted line represents 1 standard deviation (Anderson, 1994a).

Integrating Multiple Tactics into a Management System

To illustrate the integration of multiple tactics into a management system, three examples will be discussed: wheat streak mosaic virus (WSMV), wheat stem sawfly (WSS, *Cephus cinctus* Norton), and Russian wheat aphid (RWA).

Wheat Streak Mosaic Virus

Wheat streak mosaic virus causes a disease of winter and spring wheats called wheat streak mosaic. The disease also has been observed in corn, barley, and oat crops, but most frequently is seen in wheat. The symptoms of this disease are pale, yellow streaked leaves, stunted plants, and poor head and grain development. Yield losses due to WSMV in the Great Plains vary from year to year. In 1994, WSMV was reported as severe in scattered areas, from Kansas northward through Montana. If infection is severe, WSMV can cause almost 100% loss in an individual field. Yield loss is correlated with time of infection; the earlier the infection in the growth stage of the crop, generally the greater the severity of infection and greater the loss.

The vector for WSMV is the wheat curl mite (*Aceria tosichella* Keifer). The mite is tiny (<0.01 in. long), has no wings, and is carried by wind from plant to plant and field to field. The life cycle of the mite, from egg to adult, is completed in 7 to 10 d. The mite requires green plants for feeding and reproduction. If no green food hosts are available after hatching, the mite does not survive. Wheat is the preferred food for the mite and also is an excellent host for virus reproduction. In addition to wheat, however, the mite may feed and survive on various other grasses such as corn, barley, oats, foxtail millet, cheat grass (*Bromus secalinus* L.), and green foxtail.

The wheat curl mite reproduces most rapidly from 75 to 80°F. Warm, dry conditions are most favorable for mite reproduction and spread. Reproduction stops at temperatures near freezing, but the mites can survive for several months at those temperatures. Mites overwinter as eggs, nymphs, or adults in the living winter wheat crown or the crown of other perennial grass hosts.

Grass hosts other than wheat are reservoirs for long term survival of mites and virus. Severe outbreaks of WSMV are almost always associated with fall infection of winter wheat. Infected winter wheat often is the source of mites and virus from which infections develop in spring wheat.

Management of WSMV combines several tactics and is aimed at breaking the life cycle of the wheat curl mite (McMullen, 1991). First, volunteer wheat and grassy weed hosts must be destroyed at least 2 wk before planting. The 2 wk without a green host provides enough time for the mites to be without food, and thus they die prior to emergence of the new crop. The occurrence of volunteer wheat can be reduced somewhat by careful combine adjustment during harvest. However, outbreaks of WSMV often are associated with preharvest hail damage and resulting heavy production of volunteer wheat. Volunteer wheat and grassy weeds can be destroyed either by tillage or by use of chemical fallow herbicides. Control of volunteers is most effective if practiced on an area-wide basis so sources of the mite and virus are minimized.

A second management tactic is to plant at dates that will reduce the opportunity for infected mites to infest the crop. Later planting of winter wheat reduces infestations and reduces the likelihood that large populations of mites will develop in the fall. In North Dakota, the recommended planting time is 15 September or later. Planting date recommendations will vary with each state, but the most severe infections in winter wheat generally have been associated with planting too early. In contrast, the most vulnerable spring wheat crops are those planted too late. Thus, spring wheat should be planted early to avoid potential exposure to large numbers of virus-carrying mites as they move out of near-by, maturing winter wheat crops.

Host plant resistance is a third management tactic that can be used along with the first two. A number of winter and spring wheat cultivars that have some degree of tolerance to WSMV have been identified. Tolerance or resistance to the wheat curl mite also has been identified in some cultivars. These cultivars should be considered for use in areas of high risk of WSMV.

Wheat Stem Sawfly

Weiss and Morrill (1992) recently reviewed management of the WSS. This discussion is based on their review.

Adult female WSS lay one egg per stem of wheat. Upon hatching, the larva tunnels in the stem, and after completing its development, cuts a V-shaped notch at the base of the stem. Often stems break at the notch, resulting in lodging. One tactic that can be used to manage this pest in spring wheat is to plant one of the resistant (solid stem) cultivars. However, the resistant cultivars do not yield as well as the susceptible (hollow stem) cultivars. Thus, the HPR tactic is best used as a normal component of the spring wheat cropping system only in areas of low rainfall that have a history of consistently severe WSS problems. In areas where WSS problems are historically inconsistent, the best strategy is probably to plant susceptible cultivars and then harvest early, using modified harvesting techniques to reduce yield loss resulting from lodging—if it occurs.

In the case of the WSS, the historical development of typical wheat-fallow cropping systems probably favored the buildup of more severe pest problems. One important factor is that when soil moisture is low (such as was common in the wheat-wheat systems of the 1800s), wheat tends to senesce before stems reach a sufficient diameter to be preferred as oviposition sites over native grass hosts. In contrast, under more plentiful soil moisture conditions (such as occurs in wheat-fallow systems) wheat tends to produce larger diameter stems that are more attractive for oviposition. A second factor is that in wheat–fallow cropping systems, the alternating strips of wheat and fallow are typically narrow, to aid in the control of wind erosion. This pattern of land use also favors the WSS. Wheat stem sawflies overwinter in stubble and when they emerge in late May and early June, females lay eggs in developing wheat stems. Because they are relatively poor fliers, adult females must find oviposition sites close to where they emerge. Thus, narrow strips of alternating stubble and wheat present an ideal landscape for WSS, where overwintering and oviposition sites are nearby one another.

Manipulating the agricultural landscape may offer management opportunities. At North Dakota State University, ongoing work by M.J. Weiss (1995, personal communication) and associates indicates that field size and planting pattern can be altered to reduce the impact of WSS. In one system they have developed, a high yielding, hollow stem cultivar is planted in an area of perhaps several hundred acres. Around the edge of this area, a narrow strip of solid stemmed cultivar (or a nonhost) is planted. Because they are weak fliers, WSS emerging from surrounding wheat and native grass hosts cannot invade the central area planted to the susceptible (but high yielding in the absence of the pest) cultivar.

Russian Wheat Aphid

Since its discovery in Texas in 1986, the RWA has become the major pest of wheat in the western USA. It is estimated to have caused losses of nearly $1 billion in combined insecticide treatment costs and yield reductions (Webster et al., 1994). A management system employing the tactics of HPR, biological control (importation and release of BCAs and conservation of BCAs), various cultural practices, and pesticides is being developed. A resistant cultivar, Halt, has been released (Quick et al., 1995) and is expected to be widely available for growers to plant in the fall of 1996. Halt is well adapted to many of the RWA-affected areas of Colorado, Texas, Kansas, Nebraska, and Oklahoma; and resistant cultivars adapted to other infested regions are expected to be available soon. Figure 4 shows yields of a sister line to Halt and a commonly grown susceptible cultivar. While the resistant cultivar dramatically outyields the susceptible cultivar in the presence of RWA, the susceptible cultivar has a slight yield advantage when RWA are not present. Thus, producers will face management decisions regarding where and under what conditions to use the HPR

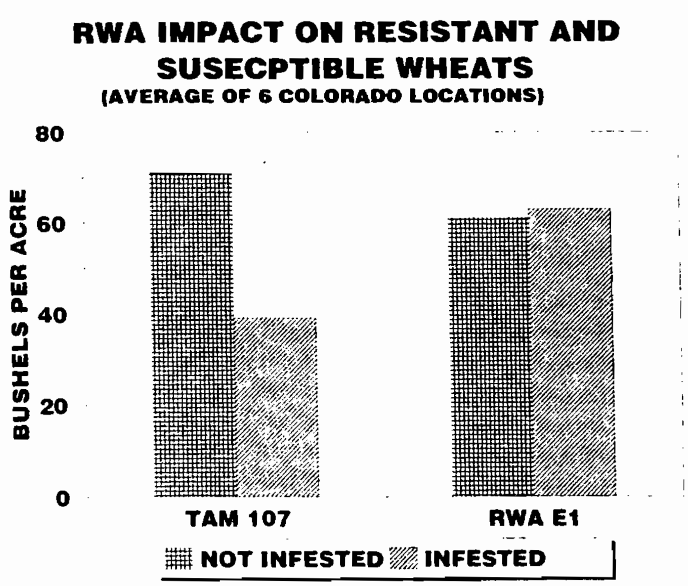

Fig. 4. Yield of TAM 107 (a standard cultivar) and RWA E1 (a cultivar with Russian wheat aphid (RWA) resistance) when uninfested or infested with Russian wheat aphid.

tactic. The development costs for Halt are estimated to be \$0.5 million, but the return on investment is expected to be 13.5 to 1 (assuming a 5 yr useful life of the cultivar, historically consistent RWA infestations, and taking into account a yield differential similar to that shown in Fig. 4).

The introduction of exotic BCAs for RWA from Europe, Asia, and Latin America has not been very effective in the Great Plains thus far, in part because establishment of the BCAs has been poor. Establishment and maintenance of BCAs in effective numbers in the landscape may be improved if releases are made into cropping systems that include crops that provide other aphid species for the BCAs to feed on during the time that wheat and RWA are essentially absent. Such systems also may favor the effectiveness of native BCAs. Two of us (Thomas Holtzer and Frank Peairs) are involved in experiments aimed at determining if BCA establishment and effectiveness is enhanced in a cropping system that includes wheat, corn, millet, and sunflowers grown in rotation. Unlike the WSS system, small field size may be a benefit in the RWA system because small fields may facilitate colonization of RWA by BCAs moving into wheat from other crops. Improving the effectiveness of biological control is an important goal because relying on HPR alone may contribute to the development of RWA biotypes that overcome the resistance in the host plant. In addition, biological control may become an increasingly important tactic in maintaining RWA below damaging levels in areas where planting resistant cultivars is not desirable.

CONCLUSIONS AND RECOMMENDATIONS

We have suggested that, to meet the needs for IPM in dryland systems, the emphasis must be on building management tactics into cropping systems. However, we also have presented substantial evidence that designing optimal cropping systems may be an overwhelming exercise in coping with complexity. Clearly, there are many interacting factors in cropping systems that must be considered. Any change in the system is likely to have significant effects, some of which will not be easy to anticipate. Many effects probably will be positive, but others are likely to be negative. How then are we to proceed toward the goal of designing effective pest management into cropping systems? The answer is obvious, but not easily accomplished.

We must concentrate our efforts at the cropping systems level, and we must build concern about pests into the design and testing of cropping systems from the beginning. IPM must not be an add-on once research and implementation are well underway. This kind of effort will require a systems approach with teams of individuals from many disciplines working together. In addition, we must find ways to include as equal partners individuals with expertise in research, extension, and implementation; and we must find ways to involve producers in the effort from the earliest stages. To be successful, we will have to overcome the many difficulties associated with such approaches. These difficulties include finding ways to fund long-term, large-scale projects, learning how to communicate with people who have different views and backgrounds or speak different disciplinary languages, and learning how to preserve the professional development and recognition of all those involved.

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