

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.

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 understand-

Table 2. Use-pattern† 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.

ing 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 con-

Alternate Host Plants of Russian Wheat Aphid in Colorado

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The Russian wheat aphid (RWA), *Diuraphis noxia* (Mordvilko), was first reported in Colorado in 1986, and since that time has caused extensive damage to the small grain crop. RWA remains an annual threat to wheat and barley production in the western United States (Webster et al., 1994).

RWA populations vary greatly within a season, between geographic locations, and from year to year. Increases in RWA abundance occur when conditions are favorable for aphid reproduction and growth. These conditions include rapid vegetative growth of acceptable host plants, which provide shelter within rolled leaves and nutrients needed for aphid growth, and warm dry weather. Declines in RWA abundance in Colorado are due largely to mortality during two critical time periods. Winter mortality is due to environmental conditions, including excessive moisture and extended or extreme cold, and occurs mainly within the fall planted small grain crop. The other period of RWA mortality occurs in the time between small grain harvest in the summer and the emergence of the next crop in the fall. This time period is characterized by high temperatures and the lack of preferred host plants, wheat and barley, when RWA must survive on alternate host plants.

RWA infest alternate host plants as alate aphids fly from maturing small grain fields. RWA flights are monitored with several Allison-Pike suction traps throughout Colorado. These traps capture aphids that fly over a 12 inch diameter tube located 26 feet above ground level (Allison & Pike 1988). Figure 1 shows the results of suction trapping from 1988 to 1990 at three sites in Colorado. The earliest peak flights in the state occur in the southeast, where small grain matures earliest. Aphid catches cease by mid July in this area. If alternate hosts are not infested by then, overwintering of RWA will be minimal. RWA flights in northeastern Colorado begin several weeks later than those in southeastern Colorado, with trap catches occurring until August. RWA flights in the Grand Valley of western Colorado start at about the same time as those in southeastern Colorado and continue throughout the growing season, although captures decline after early August. RWA infest alternate host plants throughout the summer and fall in the Grand Valley, and fall infestations in small grain fields are typically more severe than other areas of the state.

The objective of this publication is to report the results RWA overwintering host plant surveys in different regions of Colorado. Two different approaches have been used elsewhere to determine RWA host preference and suitability. Greenhouse screening studies have examined seedlings of many

grass and broadleaf species as potential host plants under controlled conditions (Kindler & Springer, 1989). Field surveys have examined established plants on roadsides, rangeland, Conservation Reserve Program (CRP) acreage, and seed production fields (Armstrong et al. 1991, Clement et al. 1990, Lajeunesse et al. 1988). Host plants utilized by RWA vary among regions and among years within regions. These differences may be explained by varying environmental conditions and genetic diversity within plant species.

Kindler & Springer (1989) tested potential host plants in a greenhouse study, and reported that RWA survived only on grasses. They did not survive on the 27 legumes and 17 forbs tested. RWA survived on seedlings of 47 of 48 cool season grass species and 18 of 32 warm season grass species during the 14 day study. The greatest reproduction was on cool season grasses, including species of *Agropyron*, *Elymus*, *Hordeum*, *Triticum*, *Bromus* and *Festuca*. Warm season grasses that RWA survived on for 14 days include species of *Leptochloa*, *Bouteloua*, *Pennisetum*, *Eragrostis* and *Buchloë*. Host suitability varies greatly within genera and even species (Kindler et al., 1993). Seedlings of 2371 plant accessions of perennial triticeae representing 8 genera, 60 species, seven subspecies and one released cultivar varied widely in RWA resistance ratings. *Leymus* and *Elytrigia* were considered moderately resistant, *Agropyron*, *Pseudoregenia*, *Elymus* and *Pascopyron* were considered tolerant to moderately susceptible, and *Hordeum* and *Thinopyron* were considered susceptible. Both Clement & Clement (1990) and Kindler & Springer (1991) demonstrated resistance to RWA in many species of *Hordeum* in greenhouse studies. Variation from susceptible to resistant exists in western wheatgrass (*Pascopyron smithii* (Rydb.) A. Löve) and slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners) (personal communication, S. D. Kindler, USDA-ARS, 1301 N. Western, Stillwater OK 74075). Kindler et al. (1991a) reported a wide range of resistance to RWA in quackgrass (*Elytrigia repens* (L.) Nevski), and that the hybrids of quackgrass and susceptible wheatgrass species were resistant. Some of the resistance to RWA in *Festuca* spp. may be due to the presence of fungal endophytes (Kindler et al. 1991b). Russian wheat aphid survival was lower of endophyte infected perennial ryegrass (*Lolium perenne* (L.)) compared with uninfected plants of the same species and variety (Clement et al. 1992). Kindler et al. (1992) used electronic feeding monitors to show that RWA feeding behavior was different on

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 (Karsen, 1982) results from germination, microbial and insect predation, and other natural mortality factors. Adding

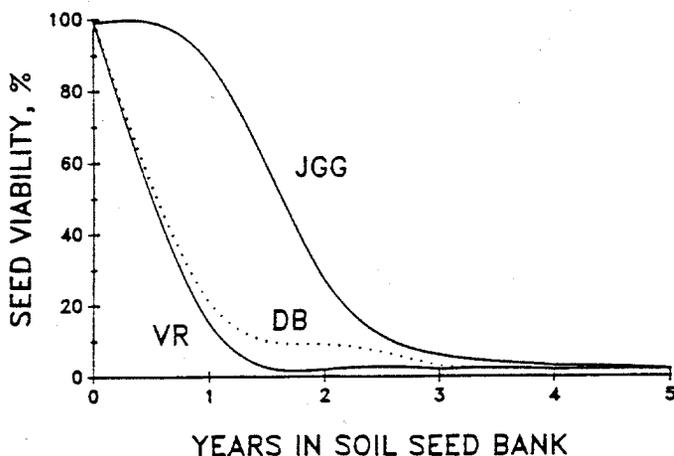


Fig. 2. Length of survival of volunteer rye (VR), jointed goatgrass (JGG), and downy brome (DB) seeds in soil (Anderson, 1994b).

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.

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.

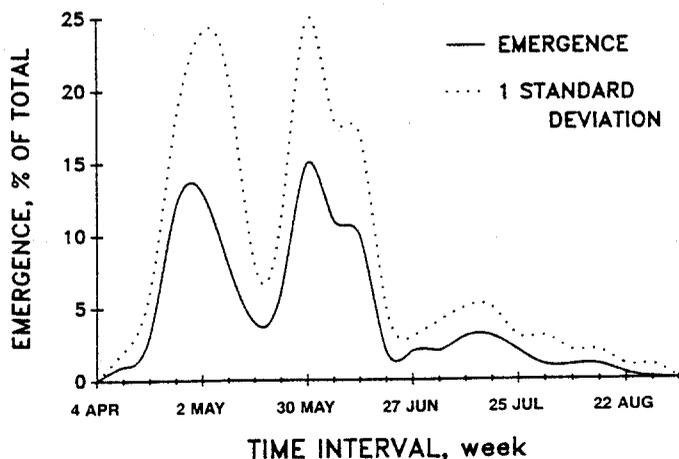


Fig. 3. Weed community emergence pattern (solid line) average over 7 yr. Dotted line represents 1 standard deviation (Anderson, 1994a).

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 prac-

ticed 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

RWA IMPACT ON RESISTANT AND SUSCEPTIBLE WHEATS (AVERAGE OF 6 COLORADO LOCATIONS)

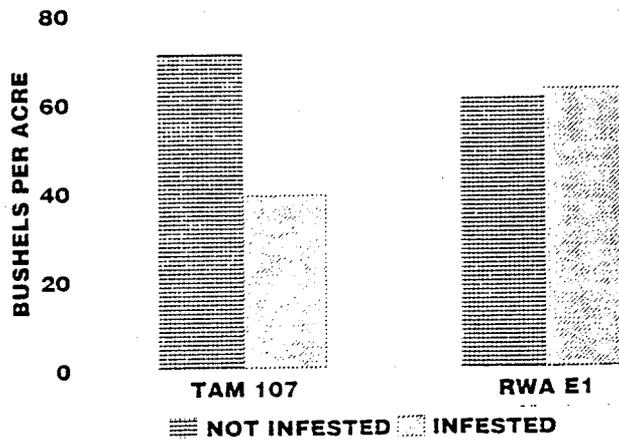


Fig. 4. Yield of TAM 107 (a standard cultivar) and RWA E1 (a cultivar with Russian wheat aphid (RWA) resistance) when uninfested or infested with Russian wheat aphid.

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.

- Anderson, R.L. 1988. Kochia infestation levels in proso millet as affected by planting date. West. Soc. Weed Sci. Res. Rep. p. 292-293. WSW, Newark, CA.
- Anderson, R.L. 1994a. Characterizing weed community seedling emergence for a semiarid site in Colorado. Weed Technol. 8:245-249.
- Anderson, R.L. 1994b. Management strategies for winter annual grasses in winter wheat. p. 114-122. In L.S. Murphy (ed.) Proc. MEY Wheat Manage. Conf., Manhattan, KS. 7-8 Mar. PPI and FAR, Denver.
- Baker, K.F., and R.J. Cook. 1982. Biological control of plant pathogens. Am. Phytopathological Soc., St. Paul, MN.
- Barton, D.L., D.C. Thill, and B. Shafii. 1992. Integrated wild oat (*Avena fatua*) management affects spring barley (*Hordeum vulgare*) yield and economics. Weed Technol. 6:129-135.
- Bauer, T.A., and D.A. Mortensen. 1992. A comparison of economic and economic optimum thresholds for two annual weeds in soybeans. Weed Technol. 6:228-235.
- Bockus, W.W., and M.M. Claassen. 1992. Effects of crop rotation and residue management practices on severity of tan spot of winter wheat. Plant Dis. 76:633-636.
- Burn, A.J., T.H. Coaker, and P.C. Jepson (ed.) 1987. Integrated pest management. Academic Press, San Diego, CA 92101.
- Burnside, O.C., C.R. Fenster, L.L. Everts, and R.F. Mumm. 1981. Germination of exhumed weed seed in Nebraska. Weed Sci. 29:577-586.
- Callaway, M.B. 1992. A compendium of crop varietal tolerance to weeds. Am. J. Altern. Agric. 7:169-180.
- Cate, J.R. 1990. Biological control of pests and diseases: Integrating a diverse heritage. p. 23-43. In R.L. Baker and P.E. Dunn (ed.) New directions in biological control. Allen R. Liss, New York.
- Cate, J.R., and M.K. Hinkle. 1993. Integrated pest management: The path of a paradigm. Natl. Audubon Soc. Spec. Rep.
- Coble, H.D., and D.A. Mortensen. 1992. The threshold concept and its application to weed science. Weed Technol. 6:191-195.
- Cook, R.J. 1994. The place for IPM in the next decade. p. 4-16. In R.J. Kuhr (coord.) Proc. 2nd Natl. Integrated Pest Manage. Symp./Worksh, Las Vegas, NV. 19-22 Apr. USDA, Washington, DC.
- Cook, R.J., and K.E. Baker. 1983. The nature and practice of biological control of plant pathogens. Am. Phytopathological Soc., St. Paul, MN.
- Cousens, R. 1987. Theory and reality of weed control thresholds. Plant Prot. Q. 2:13-20.
- Croft, B.A., 1990. Arthropod biological control agents and pesticides. John Wiley and Sons, New York.
- Dent, D. 1991. Insect pest management. CAB Int., Wallingford, UK.
- Douppnik, B., Jr. and M.G. Boosalis. 1980. Ecofollow—a reduced tillage system—and plant diseases. Plant Dis. 64:31-35.
- Eigenbrode, S.D., and J.T. Trumble. 1994. Host plant resistance to arthropods in vegetable crops. J. Agric. Entomol. 11:201-224.
- Elliott, N.C., G.L. Hein, and B.M. Shepard. 1994. Sampling arthropod pests of wheat and rice. p. 627-666. In L.P. Pedigo and G.D. Buntin (ed.) Handb. of sampling methods for arthropods in agriculture. CRC Press, Boca Raton, FL.
- Funderburk, J.E., and L.G. Higley. 1994. Management of arthropod pests. p. 199-227. In J.L. Hatfield and D.L. Karlen (ed.) Sustainable agriculture systems. CRC Press, Boca Raton, FL.
- Funderburk, J., L. Higley, and G.D. Buntin. 1993. Concepts and directions in arthropod pest management. Adv. Agron. 51:125-172.
- Gilstrap, F.E. 1996. Challenges and opportunities for importation biological control in ephemeral crop habitats. J. Biol. Control. (in press).
- Gould, F. 1991. The evolutionary potential of crop plants. Am. Sci. 29:496-507.
- Gressel, J. 1992. Addressing real weed science needs with innovations. Weed Technol. 6:509-525.
- Hatchett, J.H., and R.L. Gallun. 1970. Genetics of the ability of the Hessian fly, *Mayetiola destructor*, to survive on wheats having different genes for resistance. Ann. Entomol. Soc. Am. 63:1400-1407.
- Heinrichs, E.A. 1994. Development of multiple pest resistant crop cultivars. J. Agric. Entomol. 11:225-253.
- Higley, L.G., and L.P. Pedigo. 1993. Economic injury level concepts and their use in sustaining environmental quality. Agric. Ecosyst. Environ. 46:233-243.
- Higley, L.G., and W.K. Wintersteen. 1992. A novel approach to environmental risk assessment of pesticides as a basis for incorporating envi-

- ronmental costs into economic injury levels. *Am. Entomol.* 38 (4):34-39.
- Horn, D.J. 1988. *Ecological approach to pest management*. Guilford Press, New York.
- Karssen, C.M. 1982. Seasonal patterns of dormancy in weed seeds. p. 243-270 *In* A.A. Kahn (ed.) *The physiology and biochemistry of seed development, dormancy, and germination*. Elsevier Biomedical Press, New York.
- Krysan, J.L., D.E. Foster, T.F. Branson, K.R. Ostlie, and W.S. Cranshaw. 1986. Two years before the hatch: Rootworms adapt to crop rotation. *Bull. Entomol. Soc. Am.* 32:250-253.
- Landis, D.A. 1994. Arthropod sampling in agricultural landscapes: Ecological considerations. p. 15-31. *In* L.P. Pedigo and G.D. Buntin (ed.) *Handb. of sampling methods for arthropods in agriculture*. CRC Press, Boca Raton, FL.
- Levine, E. 1995. Rootworm problems in first-year corn: An increasing problem? p. 133-135. *In* Proc. Illinois Agric. Pesticides Conf., Champaign. 4-5 Jan. Univ. of Illinois Coop. Ext. Serv.
- Lyon, D.J., and R.L. Anderson. 1993. Crop response to fallow applications of atrazine and clomazone. *Weed Technol.* 7:949-953.
- McMullen, M.P. 1991. Wheat streak mosaic. North Dakota State Univ. Ext. Serv. Publ. 646 p.
- Nyrop, J.P., and W. van der Werf. 1994. Sampling to predict or monitor biological control. p. 245-336. *In* L.P. Pedigo and G.D. Buntin (ed.) *Handb. of sampling methods for arthropods in agriculture*. CRC Press, Boca Raton, FL.
- Pedigo, L.P. 1989. *Entomology and pest management*. Macmillan Pub. Co., New York.
- Pedigo, L.P., and G.D. Buntin (ed.) 1994. *Handb. of sampling methods for arthropods in agriculture*. CRC Press, Boca Raton, FL.
- Pedigo, L.P., S.H. Hutchins, and L.G. Higley. 1986. Economic injury levels in theory and practice. *Ann. Rev. Entomol.* 31:341-368.
- Puterka, G.J., and R.L. Burton. 1990. Aphid genetics in relation to host plant resistance. p. 59-69. *In* D.C. Peters et al. (ed.) *Proc. Symp. Aphid-Plant Interactions: Populations to Molecules*. Oklahoma Agric. Exp. Stn. Publ. MP-132.
- Quick, J.S., G.E. Ellis, R.M. Norman, J.A. Stromberger, J.F. Shanahan, F.B. Peairs, and K. Lorenz. 1996. Registration of 'Hait' wheat. *Crop Sci.* 32:210.
- Reetz, H.F., Jr. 1994. Site-specific nutrient management systems for the 1990s. *Better Crops Plant Food* 78(4):14-19.
- Schumann, G.L. 1991. Plant diseases: Their biology and social impact. *Am. Phytopathological Soc.*, St. Paul, MN.
- Schwartz, H.F., and M.A. Brick (ed.) 1993. *Colorado dry bean production and IPM*. Colorado State Univ. Agric. Exp. Stn. Bull. 548A.
- Schweizer, E.E., L.J. Wiles, D.W. Lybecker, and P. Westra. 1994. Bioeconomic modeling for weed management decisions in crops. p.135-141. *In* Proc. Great Plains Residue Manage. Conf. Great Plains Agric. Council Bull. 150.
- Shufrin, K.A., D.C. Margolies, and W.C. Black IV. 1992. Variation between biotype E clones of *Schizaphis graminum* (Homoptera: Aphidae). *Bull. Entomol. Res.* 82:407-416.
- Swinton, S., J. Sterns, K. Renner, and J. Kells. 1994. Estimating weed-crop interference parameters for weed management models. Michigan State Univ. Agric. Exp. Stn. Res. Rep. 538.
- Thill, D.C., J.M. Lish, R.H. Callihan, and E.J. Bechinski. 1991. Integrated weed management—A component of integrated pest management: A critical review. *Weed Technol.* 5:648-656.
- Webster, J.A., S. Amosson, L. Brooks, G. Hein, G. Johnson, D. Legg, B. Massey, P. Morrison, F. Peairs, and M. Weiss. 1994. Economic impact of the Russian wheat aphid in the western United States: 1992-1993. Great Plains Agric. Council Publ. GPAC-152. 16 p.
- Weiss, M.J., and W.L. Morrill. 1992. Wheat stem sawfly (Hymenoptera: Cephidae) revisited. *Am. Entomol.* 38 (4):241-245.
- Wicks, G.A., and D.E. Smika. 1990. Central Great Plains. p. 127-157. *In* W.W. Donald (ed.) *Systems of weed control in wheat in North America*. Weed Sci. Soc. Am., Champaign, IL.
- Wicks, G.A., R.E. Ramsel, P.T. Nordquist, J.W. Schmidt, and Challaiah. 1986. Impact of wheat cultivars on establishment and suppression of summer annual weeds. *Agron. J.* 78:59-62.
- Wilson, L.T. 1985. Estimating the abundance and impact of natural enemies in IPM systems. p. 303-322. *In* M.A. Hoy and D.C. Herzog (ed.) *Biological control in agricultural IPM systems*. Academic Press, Orlando, FL.