Since the beginning of agriculture, producers have compensated for the presence of insects, plant diseases, and weeds. To minimize impact of these pests, producers use a multitude of strategies, such as cultural, mechanical, and biological practices, as well as pesticides. Yet, even with this extensive arsenal of control options, producers still lose considerable crop yield due to pests (Bridges, 1994).

Because pesticides were initially so effective, producers and scientists perceived pesticides as the "silver bullet," controlling pests with one management tactic. However, this pesticide-based approach has consistently failed to achieve long-term pest management (Pedigo, 1995; Mortensen et al., 2000). A startling consequence of this single-tactic approach is development of pesticide resistance. Worldwide, numerous species of insects, plant pathogens, and weeds are now resistant to commonly-used pesticides (Holt and LeBaron, 1990). Cost of pest resistance can be substantial; herbicide resistance in wild oat (Avena fatua L.) increased costs of weed control in cereal grains $4 million (Beckie et al., 1999).

A second trend with current production systems is proliferation of pest-crop associations. A striking example occurs with corn (Zea mays L.) in the USA. Development of agrochemicals led producers to grow corn more frequently in their crop rotations; consequently, corn rootworm (Diabrotica spp.) is now so common that crop losses and control costs approach $1 billion annually (Sutter and Lance, 1991). In regions where winter wheat (Triticum aestivum L.) is the major crop, weeds with similar life cycles continuously reduce yield considerably. Examples include the brome species (Bromus spp.) and jointed goatgrass (Aegi-
lops cylindrica Host) in the USA (Wicks, 1984; Donald and Zimdahl, 1987), and rigid ryegrass in Australia (Powles et al., 1998). A similar situation is occurring with plant diseases; oilseed crops are being grown more frequently in Canada, leading to more plant diseases caused by *Scierotinia* (Bailey, 1996).

Another attribute of production systems in some countries is that production costs continue to increase, yet prices for crop products remain unchanged or even lower. If pests are not managed, yields can be significantly lower than those attainable in an ideal environment without pests (Cook and Veseth, 1991). To ensure economic survival, producers thus increase crop inputs with the goal of increasing yields to offset these costs; the final consequence, however, is a crop input treadmill. Both producers and scientists are now asking “Can we devise production systems that do not require high inputs?”

One possible solution for these concerns is to devise ecologically-based pest management (National Research Council, 1996); an approach that emphasizes prevention and pest population management (Pedigo, 1995). Production systems can be designed to lower average density of pests with tactics such as diversifying crops in a rotation. A further component of the preventive approach is to strengthen crop tolerance to pests. Crop tolerance can be achieved by selecting cultivars with pest resistance or devising fertilizer management that increases crop vigor.

With the ecologically-based approach, pesticides supplement preventive tactics rather than serve as the silver bullet. Knowledge of pest ecology is integrated with multiple control tactics, with the initial emphasis placed on systems design. Combining pest management strategies with the natural strengths of crop rotations and competitive crop canopies improves pest management such that need for pesticides is minimized (Holtzer et al., 1996; Lewis et al., 1997).

Historically, crop rotations were an integral component of pest control (Leighty 1938). Rotating crops was the primary strategy to manage root diseases of wheat (Cook and Veseth, 1991), whereas alternating small grain crops with wide row crops such as corn was a standard practice to minimize weed problems (Patriquin, 1988). However, agrochemicals led producers to rely less on crop rotations for pest management (Kurtz et al., 1984).

In recent years, there has been renewed interest among producers and scientists in exploring diverse rotations. First, crop growth can be enhanced by diversifying the crops included in rotations, which improves both yield (Crookston et al., 1991) and crop tolerance to pests (Cook and Veseth, 1991). Second, production systems that preserve crop residue on the soil surface enable producers to change crop rotations in semiarid regions (Peterson et al., 1993). Crop residue improves precipitation storage during noncrop periods, thus enabling producers to grow more crops in succession. This change in perception of crop rotation provides an opportunity to restructure cropping systems by integrating crop diversity and sequencing with our greater understanding of pest ecology (Lewis et al., 1997).

Therefore, our objective with this chapter is to explain ecological principles related to pest life cycles and management. Our ultimate goal is to suggest guidelines for producers and scientists to integrate these principles with the design of crop rotations to limit pest problems. With this approach, rotations are the foun-
dation of pest management, strengthening effectiveness of management strategies within a growing season (Lewis et al., 1997; Anderson, 1998a). For example, a system comprised of diverse rotations and ecologically-based pest management reduced pesticide input 78% over a 5-yr period, compared to the conventional production system in England (Jordan et al., 1997). Furthermore, this ecological approach will aid producers in production systems where pesticides are not used, as diverse crop sequences disrupt population growth of pests (Pedigo, 1995) and improve crop tolerance to pests (Lewis et al., 1997).

**INSECT MANAGEMENT**

**Ecological Principles Related to Management of Arthropod Pests:**

**Introduction**

This section addresses management of arthropod pests in dryland agroecosystems from an ecological perspective. The ultimate goal of such an approach is to develop pest management strategies that are both cost effective and environmentally sound. First, several ecological concepts that contribute to our understanding of how arthropod pest problems develop in dryland agroecosystems, such as niche breadth, characteristics of agricultural communities, crop islands, vegetational diversity, and natural enemy diversity, are discussed. Then, relative utility of the major pest management strategies (biological control, plant resistance, cultural practices, and chemical control) will be related to dryland production systems.

**Useful Ecological Concepts**

The niche of an arthropod pest can be defined as the set of ecological requirements, for example, food, shelter, temperature, and humidity, necessary for success. Species whose requirements allow them to be successful over a wide range of conditions are said to have a broad niche, while those that are restricted by their ecological requirements to a limited range of conditions are said to have narrow niche. Niche breadth helps define consistency and geographic scope of pest problems. Niche breadth also may be a determinant for degree of influence that the production system has on pest success.

For example, wheat midge [*Sitodiplosis mosellana* (Gehin)] can be a devastating pest of wheat, but only if the proper combination of spring soil moisture, crop development, and wind conditions during oviposition occurs. Therefore, wheat midge is a key pest only in certain parts of the Canadian prairie provinces and northern plains of the USA (Anonymous, 2006), and reaches outbreak levels in Europe only in certain years and locations (Oakley et al., 1998). Distribution and consistency of Russian wheat aphid [*Diuraphis noxia* (Mordvilko)] infestations are limited by winter temperatures and availability of summer alternate hosts. Consistent problems are thus common only in eastern Colorado and limited areas in bordering states (Elliott et al., 1998). Russian wheat aphid distribution is similarly limited by rainfall patterns and host availability in South Africa (Walters 1984). In contrast, army cutworm [*Euxoa auxiliaris* (Grote)] is widely adapted
to wheat production areas in western North America due, in part, to its wide host range and relative tolerance to temperature and precipitation extremes (Burton et al., 1980). Sunn pest *Eurygaster integriceps* Puton has a similar wide distribution in the Near and Middle East, eastern Europe, and western Asia (Critchley 1998).

In ecological terms, dryland agroecosystems are similar to early succession communities. Some characteristics of such communities are advantageous to the producer, for example, high productivity and rapid nutrient exchange. Others, such as low diversity, simple food chains, and low stability often tend to favor pest outbreaks relative to climax communities. An objective of dryland agroecosystem design thus should be to incorporate more characteristics of mature communities and fewer characteristics of early succession communities. Additionally, it should be recognized that the producer has some control, particularly over initiation and termination of events, that can help ameliorate some negative aspects of simple production systems.

Price and Waldbauer (1994) point out that crops resemble islands in several important ways and that studies of island invasion provide useful insights into pest activity in agroecosystems. The first invaders arriving at an island or a planted field tend to be r strategists rather than K strategists (r and K are terms in an equation describing population growth). R strategists are efficient early colonizers with rapid population growth and are adept at successfully exploiting a new resource such as a recently emerged crop before arrival of their natural enemies. Aphids are common pests of many dryland crops and are typical r strategists (Dixon 1998). For example, Russian wheat aphid achieves high reproductive capacity through parthenogenesis, short life cycle, birth of live young, and efficient colonization through a winged form capable of long distance, wind-aided dispersal. Contrast this to K strategist pests such as pests of trees in mature forests, with life cycles of several years and limited fecundity and dispersal capacity (Furniss and Carolin 1977). Designers of dryland agroecosystems should expect most pest problems to be caused by species with r-strategy characteristics.

The crop island concept also highlights the relationship between migration ability of pests on the nature of a pest problem. Resident species, such as western corn rootworm (*Diabrotica virgifera virgifera* LeConte) are present at seeding, and infestations tend to occur throughout the field (Sutter 1999). Such species are affected by system design; for example, crop rotation, especially if comprised of two or more nonhost crops, is a highly effective control measure for western corn rootworm.

Local immigrant species enter the crop from local sources and tend, at least initially, to be more abundant in crop margins. These species also are affected by system design, particularly regarding proximity of source crops, noncrop host plants or other harborages. For example, winter wheat commonly serves as a source of Banks grass mite *Oligonychus pratensis* (Banks) infestations in field corn in the spring, while the reverse occurs in the fall (Holtzer et al., 1984). Dryland agroecosystems designed to maximize distance between field corn and winter wheat would minimize such interactions. European wheat stem sawfly (*Cephus pygmaeus* L.) in a pest of small grains in Europe and the Middle East (Miller 1987), and has limited ability to disperse from infested stubble. This pest
would be influenced negatively by cropping systems designed to maximize the distance between previous small grains crops and newly sown crops.

Long distance immigrants arrive from relatively distant sources and tend to arrive later in crop development than resident and local immigrant species. The corn earworm \([\text{Helicoverpa zea} \ (\text{Boddie})]\) generally does not overwinter in the central and northern plains and migrates north to infest corn and sorghum in mid-to late summer (Wiseman 1999). System design would be expected to have less influence on this sort of pest problem, although distant crops should have lower colonization rates.

Andow (1991) reviewed importance of vegetational diversity in cropping systems. Plant pests, particularly those with limited host ranges, tended to be less abundant in diverse cropping systems. For example, Capinera et al. (1985) noted reduced abundance of specialist pests in a sweet corn/dry bean \([\text{Phaseolus vulgaris} \ L.]\) strip intercrop compared to two corresponding monocultures, while generalist pests were unaffected. Crop diversification thus would be expected to be more effective against dryland crop pests with limited host ranges such as wheat midge or sunflower stem weevil \([\text{Cylindrocopturus adspersus} \ (\text{LeConte})]\) than against those with broad host ranges such as army cutworm and pale western cutworm \([\text{Agrotis orthogonia} \ \text{Morrison}]\). However, mobility of a given species may limit the influence of vegetational diversity. For example, highly mobile pests such as adult lepidopterans may be less affected by diversity than less mobile pests such as aphids and spider mites. Although many of the studies analyzed by Andow (1991) were of more complex polycultural cropping systems than those used in dryland production systems, it seems clear that crop diversification has pest management benefits that should be considered.

Andow (1991) presented two hypotheses to explain suppression of crop pests in more diverse cropping systems. The enemies hypothesis states that natural enemies are more abundant in more diverse cropping systems and therefore biological control is enhanced. The resource concentration hypothesis states that plant pests are more likely to colonize hosts that occur in large, dense, or pure stands. Andow concluded that, while both mechanisms occur, there was more evidence to support the importance of resource concentration in pest suppression in diversified cropping systems.

Nonetheless, natural enemies can be important stabilizing factors in a community. Generalist predator and parasitoid species tend to be more stabilizing than specialists, although the latter are more efficient. Where few species are involved, generalists assume even greater importance (Price and Waldbauer 1994). Dryland cropping system design thus should emphasize attraction and retention of generalist predators and parasitoids.

**Available Tactics and Relative Utility for Dryland Cropping Systems**

Biological control is the use of one organism to control another. In the case of arthropod pests, the controlling organisms usually are predators, parasitoids, or pathogens. Holtzer et al. (1996) assessed pest management tactics and found both classical (importation and release) and conservation biological control important considerations in the design of dryland cropping systems. Conservation
biological control is emphasized here because it is a part of day-to-day cropping system management while classical biological control often involves just a limited number of releases at a given location. Augmentative biological control was thought to be prohibitively expensive and not sufficiently preventive in nature to meet the requirements of effective pest management in dryland cropping systems.

The general advantages of conservation biological control are low cost and low environmental impact. Conservation biological control can be quite effective; for example, the Texas Agricultural Extension Service recommends against insecticidal treatment of greenbug \([\text{Schizaphis graminum (Rondani)}]\) in sorghum \([\text{Sorghum bicolor (L.) Moench}]\) if more than 20% are parasitized (Cronholm et al., 1993). However, conservation biological control has limitations as well. Natural enemies have ecological requirements as do their prey. Those with narrow host ranges may be more difficult to maintain in a production system. Also, natural enemy species with broad host ranges may be more easily retained than those that rely on a limited number of host species for food.

Design of dryland agroecosystems should recognize the importance of conservation biological control and niche requirements of important natural enemy species. As indicated above, predators and parasitoids with wide host ranges appear to be more effective in relatively simple communities such as annual cropping systems. Those with wide geographic distribution, indicative of broad niche species, should be emphasized as well.

Plant resistance, or the use of varieties resistant to arthropod pests, also was identified by Holtzer et al. (1996) as an important design consideration for dryland agroecosystems. Resistant varieties are low in cost and environmental impact. This management approach has been used successfully against important arthropod pests of several dryland crops, for example, greenbug, Hessian fly \([\text{Mayetiola destructor (Say)}]\), Russian wheat aphid, wheat curl mite \([\text{Aceria tosichella Keifer}\] ), and wheat stem sawfly \([\text{Cephus cinctus Norton}\] ) in small grains (Miller 1987; Webster and Kenkel 1999).

The utility of resistant varieties in dryland cropping systems is limited by the time required to develop effective varieties. For example, the first North American wheat cultivar resistant to Russian wheat aphid was developed in a relatively short period of 7 yr (Quick et al., 1996). Additionally, biotypes, or pest races capable of overcoming resistance, are a concern with several pests, including greenbug (Porter et al., 1997) and Hessian fly (Sosa 1981). Furthermore, in some cases plant resistance can interact negatively with natural enemies (Reed et al., 1991), although positive interactions have been reported as well (Starks et al., 1972).

Design of dryland agroecosystems should emphasize varieties that are resistant to key pests. Varieties that interact positively with biological control agents are desirable. However, it seems likely that negative interactions would be less important with generalist natural enemies than with more specialized species.

Many cultural practices can be modified to disfavor arthropod pests of dryland crops or to favor their natural enemies, and could be incorporated into cropping system design. Key practices include tillage, crop diversification (discussed above), sanitation, and timing of seeding and other operations. Tillage effects on arthropod pests have been reviewed, with roughly equal proportions of species
PEST MANAGEMENT WITH ROTATION DESIGN

being unaffected, affected negatively or favored by reductions in tillage (Stinner and House, 1990). However, two important generalist predator groups, spiders and ground beetles, were much more abundant in reduced tillage soybean (*Glycine max* Merr.) than in the conventionally tilled crop in Georgia (House and Stinner 1983) and in cereals in Europe (Glen 2000). Reduced tillage should be emphasized in dryland cropping system design for its potential in favoring generalist predators, even though its overall effect on pest abundance seems limited.

Sanitation, primarily management of volunteer crop plants, is an important cultural practice in dryland crops because these plants often serve as sources of initial infestation for resident and local immigrant arthropod pests. For example, volunteer management is important in management of several key wheat pests (Peairs 1998). Adjustment of seeding dates to delay emergence until pest activity ceases or to avoid susceptible crop growth stages during peak pest activity is another cultural practice used with many dryland crop pests such as Hessian fly (Hatchett et al., 1987), Russian wheat aphid (Peairs 1998), sorghum midge (*Contarinia sorghicola* (Cocquillet)) (Wiseman and McMillian 1969), and wheat curl mite (Hatchett et al., 1987). Timing of other practices, particularly harvest, also has potential in pest management in dryland crops. Cultural practices are preventive and generally low in cost and environmental impact and therefore should be important elements in dryland cropping system design.

Insecticide and miticide treatments for arthropod infestations in dryland crops are relatively expensive and may have other undesirable effects such as mortality in natural enemy populations. However, treatments are effective, fast acting, and often the only management option for addressing existing infestations. While insecticide and miticide treatments should not be considered as part of dryland cropping system design, they should be recognized as useful tools for management of infestations that occur in spite of preventive measures. Pest species least affected by cropping system design, that is, broad niche species with wide host ranges and high mobility such as army cutworm or several grasshopper species, are probably more likely to require chemical control. The pesticide and application method should be as selective as possible, to minimize natural enemy mortality. In addition, treatment decisions should be economically justified to avoid unnecessary applications.

**Conclusions**

Arthropod pests of dryland crops should be assessed for their potential to be affected by cropping system design. Pests with narrow niches, limited host ranges, and limited mobility are more likely targets. Broadly adapted natural enemies with wide host ranges seem more desirable in these systems. Vegetational diversity, resistant varieties, reduced tillage, and alternate host management should be emphasized as design elements. Chemical controls should be part of the system, reserved for the arthropod pest species least affected by management practices designed into the system. Insecticide and miticide treatments should be as selective as possible, to minimize natural enemy mortality.
PLANT DISEASE MANAGEMENT

Ecological Principles Related to Plant Diseases

Plant diseases are a natural component of dryland agroecosystems, but their prominence in the system is dependent on interactions among three main factors, namely the pathogen, a susceptible crop, and a conducive environment. This is known as the disease triangle (Fig. 7-1). Since it requires absence of only one factor to prevent disease development, we have learned to manage our disease problems by manipulating one or more points on the disease triangle. For example, we may manage plant diseases by changing attributes of the host factor (i.e., living plant and crop residue) with cultivar-based genetics (i.e., resistance) or by diversifying with nonsusceptible crop species (i.e., nonhosts in rotation). We may modify the environmental factor (abiotic and biotic aspects) by making the microenvironment more or less amenable to pathogens using cultural practices such as tillage, row spacing, or planting date.

Ideally, the first line of defense against plant diseases should target weak links in the pest’s life cycle to prevent pathogen infection, limit pathogen distribution, and reduce pathogen abundance. Crop rotation has an integral role in prevention of disease by targeting the pathogen stages. There are four stages in the disease development cycle where pathogens may be managed with rotation design and other cultural practices: disease initiation, disease progression, disease spread, and survival. Principles for managing the pathogens at these stages and the practices related to rotation design will be discussed. Examples will be limited

![Diagram of the disease triangle and attributes of the pathogen, host, and environment that may be targeted for disease control.](image)

Fig. 7-1. The disease triangle and attributes of the pathogen, host, and environment that may be targeted for disease control.
to fungal pathogens since these comprise the dominant plant diseases under dry-land agriculture.

1. Disease Initiation

Disease Principle: Reduce Primary Inoculum. The disease initiation stage involves the first contact of pathogen inoculum (i.e., any part of the pathogen that is infective, such as mycelium or spores) with a plant. Primary inoculum is present when the crop emerges, resulting in early season infections. Source of primary inoculum for many diseases is crop residue or soil that is in close proximity to the emerging crop. Crop rotation can reduce levels of primary inoculum of most stubble-borne and soil-borne diseases. Examples of stubble-borne diseases are leaf spots (i.e., septoria, tan spot, net blotch, and scald) of cereals; blackleg of canola; ascochyta blight, and anthracnose of pulse crops. Some soil-borne diseases are sclerotinia stem rot of oilseed and pulse crops; take-all, common root rot, and fusarium root rot of cereals; and pythium root rot of many crop types.

Rotations where the same crop is grown year after year have higher levels of inoculum, more disease symptoms, and greater yield losses than those with more diverse rotations. The incidence of scald and net blotch on barley was higher after 5 yr of continuous barley production than after rotation with wheat and canola (Arvidsson 1998). The incidence of root rot caused by Microdochium nivale (Ces. Ex Berl. & Vogl.) Samuels and Hallett increased when wheat and barley were each grown continuously (Sturz and Bernier 1989; van Leur 1993). Sutton and Vyn (1990) found that the density of pseudothecia (overwintering reproductive structures that produce ascospores) of Pyrenophora tritici-repentis (Died.) Drechs. increased with density of the wheat residue (i.e., comparing two sequential wheat crops to wheat—soybean), and the disease it caused (tan spot) was moderate or severe only when wheat residues accumulated on the soil surface. Leaf spot diseases in wheat resulted in 28% less yield in the second year of growing wheat than in the first year of growing wheat (Bailey and Duczek, 1993).

After the crop has been harvested, Pyrenophora tritici-repentis usually grows saprophytically on host debris producing hyphal fragments, conidia, and ascospores. Shuh (1990) demonstrated that residue-borne ascospores of P. tritici-repentis serve as the primary inoculum in the spring after the overwintering period resulting in an earlier onset of tan spot and higher disease severities on winter wheat growing in Oklahoma. Initial infections occurred in the spring from ascospores, and not from conidia released the preceding fall. Conidia usually infect after air temperatures reach 20 to 30°C, and sustain the epidemic with secondary inoculum throughout the growing season. Residue-borne inoculum caused clumped disease patterns arising from point-source infections whereas airborne inoculum released from nearby fields caused random disease patterns. Spatial pattern of disease distribution can differentiate the mechanisms of spread.

Greatest risk of severe disease loss occurs when abundant primary inoculum is placed close to the crop. Adee and Pfender (1989) tested this hypothesis by applying four levels of primary inoculum of P. tritici-repentis (number of ascocarps on straw residue ranging from 0, 10^2, 10^3, and 10^4 per square meter plot) to winter wheat in the fall. The highest level of primary inoculum increased the
area under the disease progress curve and reduced yield relative to the control by 10 to 27% in 2 yr. This study demonstrated that local primary inoculum level has an impact that persists throughout the growing season, beyond infections that result from secondary air-borne inoculum occurring later in the season.

A comparison of seed vs. stubble-borne inoculum of ascochyta blight (Ascochyta lentis Vassilievsky) on lentil (Lens esculenta Moench J.) showed that very little disease developed when infected seed was the only source of inoculum in contrast to early, severe epidemics resulting in fields with infected lentil stubble. In stubble fields, the epidemic started as seedlings emerged and continued to develop throughout the season. When infected seed was planted in fields without stubble, transmission of disease from seeds to seedlings was slower and more dependent on environmental conditions to start the epidemic (Gossen and Morrall 1986).

Not all types of primary inoculum may be controlled by crop rotation. Seed-borne diseases such as those caused by Ascochyta on lentil seed (as in the above example) or smut diseases of cereals and grasses are examples. The benefit of crop rotation also may be limited by diseases with airborne spores, which spread from adjacent fields or are transported from further distances. The placement of this type of inoculum in a field is unpredictable because it is determined by wind movement. For example, each year infection of cereal crops by rust pathogens in Canada are determined by spores being transported by prevailing winds from the southern plains in the USA. These rust pathogens do not overwinter in Canada because their life cycle requires infection of an alternate host species (that do not exist in Canada) for production of survival structures able to withstand the cold winter temperatures. In a rotation study conducted in Saskatchewan, the disease known as mycosphaerella blight of field pea (Pisum arvense L.) was present every year, even though field pea was only used in 1/12 of the plot area in any year and the field site had no prior history of pea production (Bailey and Gossen, personal communication, 2000). This pathogen flooded the site each year via wind-borne ascospores from infected residue in adjacent fields.

2. Disease Progression

Disease Principle: Prevent Infection. Symptom development in the host is the product of the infection process that begins with adhesion of pathogen to the host, followed by penetration of the host by the pathogen and ramification of the pathogen through host tissues. In order for these steps to occur, the pathogen must be virulent on the host. There will be no infection or disease progression if the pathogen is avirulent. Therefore, knowledge of a pathogen's virulence characteristics and host range should be used in rotation design.

Pathogens with limited host range are easiest to manage by crop rotation. If the pathogen cannot survive in the absence of the host and has a limited saprophytic ability then its decline will be rapid. Pyrenophora tritici-repentis is known as a pathogen exclusively to wheat. In Saskatchewan, incidence of P. tritici-repentis on wheat was lower in a rotation of canarygrass (Phalaris canariensis L.)-sunola (Triticum X Helianthus)-wheat-lentil compared to rotations of wheat-canola (Brassica napus L.)-wheat-lentil or wheat-pea-wheat-lentil. Even
though canarygrass is considered similar to wheat for crop rotation purposes, there are no reports of Pyrenophora pathogens on canary seed in Canada (Bailey et al., 2000a). In this region, it takes 2 yr of cropping with a noncereal host after growing wheat to reduce disease caused by P. tritici-repentis (Fernandez et al., 1998). Careful planning of cropping sequences is necessary when pathogens use similar crop types as hosts. The wheat pathogen Stagonospora nodorum (Berk.) Castellani & E.G. Germano (causing septoria nodorum blotch) also infects and sporulates on barley (Hordeum vulgare L.) residue so wheat should not follow wheat or barley and barley should not follow barley or wheat in rotation (Duczek et al., 1999).

Sclerotinia sclerotiorum (Lib) De Bary (causing sclerotinia stem rot) is a pathogen with an extremely broad host range. It is capable of infecting at least 408 species in 278 genera of both dicotyledonous and monocotyledonous plants (Boland and Hall, 1994). Some crops have higher susceptibility to the pathogen—sunflower (Helianthus annuus L.), field pea, bean, and canola are highly susceptible. Crops such as cereals, grasses, alfalfa (Medicago sativa L.), potato (Solanum tuberosum L.), and flax (Linum usitatissimum L.) are more resistant. Short rotations using susceptible crops increase risk of sclerotinia stem rot. Canola in rotation with pea and bean had a higher incidence of stem rot (49%) than canola with potato and bean (10%) (Davies 1991). Crops like pea increase risk of this disease because numerous sclerotia (long-term survival structures) are produced along the stems and are released to the soil or mixed with seed during harvest. This adds large quantities of inoculum to the soil that infects many host species when present. Survival characteristics of sclerotia are discussed later.

Some pathogens display different levels of aggressiveness or physiological specialization, adding complexity to population structure. Knowledge of these characteristics provide opportunities for control with either resistant cultivars or selection of crop type. Continuous cropping may shift aggressiveness of a pathogen population over time. Conner and Atkinson (1989) showed that after 5 yr of continuous cropping with a susceptible wheat cultivar, soil-borne population of Bipolaris sorokiniana (Sacc. in Sorok.) Shoemaker (causing common root rot) changed from initially being weakly virulent to becoming highly virulent on wheat. Similarly, in another field after 5 yr of continuous cropping of susceptible barley, soil-borne population of B. sorokiniana was more virulent to barley than to wheat even though samples of the pathogen population in soil taken before growing barley were weakly virulent to barley and highly virulent to wheat. Another study compared aggressiveness of isolates of B. sorokiniana taken from a field continuously cropped to spring wheat for more than 100 yr to those from commercial fields in North Dakota cropped to wheat every 2 to 4 yr (El-Nashaar and Stack, 1989). There was a continuous range in degree of aggressiveness (from low to high) of cultures from both populations, but mean disease rating of wheat grown in soil that had been continuously cropped to wheat was 2.38, whereas mean disease rating in commercial fields was 2.16. Frequency distributions of fungal isolates by aggressiveness category in the two cropping systems were different; there were more highly aggressive isolates from continuous wheat.

In most situations, monoculture leads to increases in plant pathogens and disease severity, however there are a few rare situations, where the disease de-
clines with continued cropping, such as with take-all and cereal cyst nematode on wheat (Cook and Veseth, 1991). Take-all decline may be observed in the third, fourth, or fifth year of a wheat crop, after severe infestations have occurred. The pathogen remains virulent in soil, but is suppressed by other microorganisms in the root zone. Cereal cyst nematode follows a similar pattern of increasing pest populations in the first few years of continuous wheat production. Number of nematodes then drops to below the economic threshold due to an increase in one or more soil fungi that kill cysts and eggs of the nematode.

3. Disease Spread

**Disease Principle: Reduce Pathogen Buildup.** Secondary inoculum is produced from primary infections and results in multiple disease cycles throughout the growing season. Numerous sporulation cycles increase disease severity on plants during the growing season and sustain an epidemic that develops into higher inoculum levels on residue after harvest. Host susceptibility affects rate of sporulation during the growing season, thereby increasing spore load to the soil and disease severity on plants and residue, thus reducing crop yield.

In soil, populations of *B. sorokiniana* increased when crops of wheat, barley, or triticale (*X Triticosecale*) were grown, remained static with oat (*Avena sativa* L.), safflower (*Carthamus tinctorius* L.), and chickpea (*Cicer arietinum* L.), and declined with buffelgrass (*Cenchrus ciliaris* L.), alfalfa, mung bean (*Phaseolus aureus* Roxb.), sorghum, sunflower, millet (*Panicum miliaceum* L.), and fallow. Disease severity of common root rot in wheat was reduced relative to levels on continuous wheat when wheat was planted after safflower, sorghum, mung bean, alfalfa, and buffel grass. Disease levels in wheat following barley, triticale, oat, chickpea, millet, and sunflower or fallow were similar to those with continuous wheat. Legumes reduced the population of *B. sorokiniana* to 16% of its original level in soil after 2 to 5 yr (Wildermuth and McNamara 1991). Therefore, pasture legumes and some perennial grasses are effective in reducing disease severity and soil populations of the pathogen.

On plant tissues, *B. sorokiniana* sporulates more on crowns of cereal crops [such as wheat, barley, oat, triticale, rye (*Secale cereale* L.), and canary seed] and wheatgrass species than on annual pulse crops [faba-bean (*Vicia faba* L.), field pea, and lentil, oilseeds crops [canola, flax, mustard (*Brassica* spp.), safflower, and sunflower], forage grasses [brome grass (*Bromus inermis* L.), canarygrass, wild rye (*Secale spp.*) and forage legumes [alfalfa, clovers (*Trifolium* spp.), birds-foot trefoil (*Lotus corniculatus* L.), cicer milkvetch (*Astragalus cicer* L.), and sainfoin (*Onobrychis viciaefolia* L.)] (Duczek et al., 1996). Rotations that alternate cereals with broad-leaved crops, such as wheat-canola-wheat-lentil or wheat-pea-wheat-lentil have similar levels of common root rot and yield in the wheat phases because the rotations are similar in terms of their potential for sporulation on residue and ability to return similar quantities of inoculum to the soil (Bailey et al., 2000a). Rotations that predominately use cereals and grasses may experience yield losses from root diseases. A yield reduction of 16% in spring wheat was observed in a rotation using fallow-spring wheat-spring wheat-hay/grass mixture for 3 yr compared to wheat yields from a rotation using spring wheat-spring
wheat-lentil (Bailey and Duczek, 1993). In each of 3 yr, growing barley after barley reduced yield in the second year by an average of 11% (Bailey et al., 2000b).

4. Survival

**Disease Principle: Reduce Primary Inoculum Carryover.** Fungi survive in soil, on plant debris, on roots, xylem vessels, dead fruits, and buds of perennial plants and weeds, on or in seeds, tubers, and insects. They develop unique structures (i.e., mycelium, conidia, oospores, chlamydospores, pseudothecia, perithecia, sclerotia) that permit survival under adverse conditions from one to several years as either a saprophyte or in a resting stage. Dependence of a pathogen on a crop, its competitive nature, and longevity of survival influences effectiveness of crop rotation. We should not expect to eliminate a pathogen from the system, but reduce inoculum level to below the economic threshold so disease risk is lowered.

When winter wheat is sown in an area before spring cereals have matured, wheat streak mosaic virus can become a problem because the virus’s vector (a mite) moves from maturing spring cereals to winter wheat seedlings which act as an overwintering host for the virus-infected mite. A short break of 1 wk between crop harvest and seedling emergence and control of volunteer cereals and grasses can reduce risk of infection, since the mite requires a living host, and not residue, to survive. Incidence of wheat streak mosaic virus in both spring and winter wheat was 47% in a continuous wheat/fallow system (fallow-spring wheat-spring wheat-winter wheat), 10% under spring wheat-spring wheat-flax-winter wheat, and 8% under pea-spring wheat-winter wheat-flax rotations. Yield loss in continuous wheat/fallow was 52% (Bailey and Duczek, 1993).

Crop rotation is less effective with pathogens that are competitive or have a strong saprophytic ability. *Fusarium graminearum* Schwabe. and *B. sorokiniana* (a complex of fungi causing crown rot and common root rot) were isolated from field residues of wheat, barley, oat and black oat grown under conservation tillage, whereas *Pyrenophora avenae* Ito & Kurib. was only isolated from residue of *Avena* spp. Percentage incidence of *F. graminearum* was similar among residues from all plant species. Level of *B. sorokiniana* in plant residues was lower in *Avena* spp. than other cereals (Fernandez and dos Santos, 1992). Similarly, *B. sorokiniana* and *S. nodorum* Müller were less frequently isolated from soybean residue than *F. graminearum* (Fernandez and Fernandes, 1990). *Fusarium graminearum* was a stronger saprophyte than either *B. sorokiniana* or *S. nodorum*. It has also been observed that *B. sorokiniana* has difficulty colonizing tissues occupied by other fungal species, such as *P. avenae* on *Avena* spp. (Fernandez and dos Santos, 1992) and *Fusarium* spp. on wheat internodes (Tinline, 1977). *Bipolaris sorokiniana* was less competitive than other fungal species. Therefore, rotation will be most effective in reducing inoculum levels of *P. avenae*, moderately effective for reducing *S. nodorum*, and *B. sorokiniana*, and least effective for reducing *F. graminearum*, which had the highest competitive saprophytic ability (Fernandez and Fernandes, 1990).
The length of a recommended crop rotation may be influenced by longevity of pathogen survival. In Australia, Merriman et al. (1979) observed that 60% of sclerotia from *S. sclerotiorum* survived for more than 17 wk when left on the soil surface compared to 42% survival when buried. Microbial predation helped to reduce survival of overwintering structures. Sclerotia that formed on the exposed, outer surface of bean stems had three times more fungal colonists than sclerotia that developed inside the stem. Survival of exposed sclerotia was 40% after 17 wk buried in the soil whereas sclerotia in stems had more than 75% survival. In Canada, the half-life of sclerotia is estimated at 18 mo, but even a 5-yr absence of susceptible crops is not considered adequate to reduce number of sclerotia in soil to avoid high levels of infection in highly susceptible crops like canola (Martens et al., 1988).

*Bipolaris sorokiniana* survives as conidia in soil or mycelium in cereal and grass residue or roots. Disease incidence and intensity are correlated to inoculum density in soil, but relatively low densities (20–160 conidia per gram of soil) are needed to cause maximum disease (Duczek et al., 1985; Tinline et al., 1988). Number of conidia on residue of wheat and barley sharply decreased over one winter period in Saskatchewan, but the pathogen was able to sporulate at low levels after at least two winters on residue (Duczek et al., 1999). One to 2 yr between cereal crops is usually recommended.

The recommended rotation length is often based on time required for decomposition of infected residue. In Syria, the incidence of septoria leaf blotch was about 60% in wheat planted into 1-yr-old stubble, but <20% when planted into 2-yr-old infested stubble (Obaedo et al., 1999). Factors such as climate or tillage influence rates of decomposition (Summerell and Burgess 1989). In Australia, *Fusarium graminearum* was recovered after 104 wk from wheat stubble retained on the surface but only recovered after 8 wk from stubble that was buried in nylon bags. Survival of the fungus was correlated with decomposition rate of wheat stubble. Decline in recovery of the fungus was more rapid in the cv. Kite, which decomposed at a faster rate than cv. Suneca (Summerell and Burgess 1988). Canola stubble is more fibrous and takes longer to decompose, so even though number of ascospores of *Leptosphaeria maculans* (Desm.) Ces. et de Not. (causing blackleg) released from a given quantity of canola residue declines with each successive year, 3 or 4 yr between canola crops is recommended for control of blackleg (Gugel and Petrie, 1992).

**PRINCIPLES OF ROTATION DESIGN FOR DISEASE CONTROL**

Crop rotation is a knowledge-based preventative method for disease management. Its successful application merges identification of potential disease problems and economic constraints of production with knowledge of the pathogen’s biology, growth and survival, host range, and crop agronomics. Crop rotation for disease control has limitations. It is not a panacea and does not provide a quick fix if a disease epidemic becomes established. However, it does provide benefits under both low and high disease pressure and, when used in conjunction with
other disease management practices, lowers risk of needing costly pesticide inputs.

Crop rotation does not control all pests equally. It is not effective against diseases where infection is initiated by airborne inoculum that is dispersed over long distances by wind, or by exclusively seed-borne diseases, or diseases of perennial crops. It is less effective for diseases that survive long periods in soil without a living host, or diseases that have a broad host range. It is most effective against pathogens that originate in a field on crop residue or are soil-borne, pathogens with a narrow host range, and pathogens that decline substantially within a year or two of the host being removed.

Crop rotation affects both detrimental and beneficial microorganisms. The longer a microorganism is in contact with a host, the greater the risk of changing the population structure by selecting for more aggressive and competitive strains. Better control from crop rotation may be expected with greater differences between crops in a rotation sequence. Shorter rotations of 2 to 4 yr should alternate cereal with noncereal or broad-leaved crops using different species of cereal, oilseed, and pulse crops in each year. Rotations may be planned by estimating rate of stubble decomposition, and not replanting to the same crop species until residue has substantially decreased. This principle is most easily applied in rotations of 4 to 7 yr or longer, and with inclusion of perennial crops such as alfalfa, clovers, and grasses. The purpose of crop rotation is to achieve equilibrium below the economic threshold of the disease, but there will be crests and troughs along the way. Strategies that use time and crop diversity will come closer to achieving that equilibrium.

WEED MANAGEMENT

Weeds display characteristic growth patterns during various phases of their life cycle. Cultural strategies can be devised to disrupt these patterns, consequently reducing weed densities and improving crop tolerance to weeds. Examples will be discussed based on a generalized life cycle for annual weeds comprised of four stages, seeds in the soil seed bank, seedlings, mature plants, and seed produced by plants (Fig. 7-2). Impact of cultural practices on weed dynamics also will be related to design of crop rotations, with the goal of integrating cultural practices and rotational options into weed management systems.

Seed Bank

Soils of production fields contain a reservoir of weed seeds, which is termed the soil seed bank; this reservoir is the source of weeds infesting crops. Weed seed enters the seed bank in a multitude of ways, such as with crop seed at planting time, or transported by wind, water, animals, or machinery. However, the key contribution comes from weeds producing seeds during the growing season (Roberts, 1981); thus, a field's cropping history mainly determines species composition of the seed bank (Haas and Streibig, 1982). For example, monoculture rotations lead to seed banks comprised mainly of one or two weed species, such as occurs
with the winter wheat–fallow rotation. Prevalent species in these seed banks are downy brome (Bromus tectorum L.) and jointed goatgrass, winter annual grasses with similar life cycles to winter wheat (Holtzer et al., 1996). In contrast, rotations comprised of a diversity of crops lead to a diverse seed bank community, without predominance of one or two species (Anderson et al., 1998).

A second characteristic of seed banks is the natural decline of live (viable) seed. Seed viability in soil decreases exponentially over time, with a dramatic decline occurring during the first 2 yr after seeds enter the seed bank (Roberts, 1981; Egley and Williams, 1990). Loss of viable seeds results from germination, death by microbial or faunal consumption, or natural causes (Harper, 1977). For example, viable seed of two summer annual grass weeds, green foxtail [Setaria viridis (L.) Beauv.] and longspine sandbur [Cenchrus longispinus (Hack.) Fern.], was <10% after 2 yr in the seed bank (Fig. 7–3a). In contrast, seed viability of both species was threefold greater after 1 yr in the seed bank compared to 2 yr. A similar trend occurs with downy brome and jointed goatgrass; <5% of seed was viable after 3 yr in the seed bank (Fig. 7–3b). This rapid loss of seed viability is characteristic of most annual weed species (Roberts, 1981).

**MANAGEMENT STRATEGIES RELATED TO THE SEED BANK**

Because species composition reflects cropping history and seed viability declines rapidly, rotations can be designed to take advantage of the natural decline of seed bank densities (Anderson, 1998a). Froud-Williams et al. (1984) suggested that the time a crop is planted is probably the main factor determining composition of weed flora infesting a crop. Thus, diversifying crops with different growing seasons in a rotation leads to different planting dates, which disrupts the life cycles of predominant species in the seed bank.

An example of this approach occurs in the winter wheat region of the USA (Holtzer et al., 1996). To manage winter annual grasses in wheat, producers include summer annual crops such as corn, sorghum, or proso millet in the rotation to lengthen time between wheat crops. Rotations such as wheat-corn-fallow or
wheat-corn-proso-fallow are effective because the time interval before the next wheat crop favors natural decline of seed viability in soil, consequently reducing future weed densities. Seedlings of jointed goatgrass or downy brome, both winter annual grasses, are easily controlled during noncrop periods between summer annual crops, thus preventing seed production and entry to the seed bank.

Rotations designed to favor seed bank decline of winter annual grasses also helps control summer annual weeds. This trend was demonstrated in a long-term rotation study comparing various combinations of summer and winter annual crops (Anderson, 1998a). Proso millet, a summer annual crop, was included in four rotations; continuous proso (M-M), winter wheat-proso-fallow (W-M-F),

Fig. 7-3. Persistence of seed viability of (a) green foxtail and field sandbur, and (b) downy brome and jointed goatgrass, when seed remains within the top 3 cm of soil (adapted from Dawson and Burns, 1975; Donald and Zimdahl, 1987; Boydston, 1990; Anderson, 1998a).
Fig. 7-4. Biomass of green foxtail and longspine sandbur in proso millet for four rotations at a semiarid site, Akron, CO (W: winter wheat; M: proso; C: corn; and F: fallow). Study was initiated in 1990, with weed biomass measured in 1997 and 1999. Data averaged across years; bars with the same letter are not significantly different based on Fisher's LSD (0.05) (adapted from Anderson, 1998a).

After 8 yr, biomass of these grasses was 180 g m\(^{-2}\) in continuous proso (Fig. 7-4). In contrast, weed biomass was sixfold less in W-M-F, a rotation with only one summer crop in 3 yr. Comparing W-C-M-F with W-C-M, weed biomass was threefold less in the 4-yr rotation. Both W-M-F and W-C-M-F have 2 yr in the rotation when green foxtail and longspine sandbur can be easily controlled before seed is produced, thus favoring rapid decline of their seed bank density (Fig. 7-3a). These results show that balancing crops with different growing seasons in a rotation, with at least 2 yr of crops with similar growing seasons in a row, can accrue a several-fold benefit for managing both winter and summer annual weeds.

In semiarid regions, rotations comprised of four different crops accrue other benefits as well as managing weeds. Grain yield is increased due to the rotation effect, time management is improved, and economic risk is minimized by diversity of crop products (Kurtz et al., 1984; Anderson, 1998a).
Seedling Emergence

Most annual weeds typically emerge during certain periods of the year (Egley and Williams, 1990). For example, jointed goatgrass, a winter annual grass, emerges in late September through early November, with a secondary flush of seedlings emerging in early spring (Anderson, 1998b). In contrast, velvetleaf (*Abutilon theophrasti* Medik.), a summer annual broadleaf species, emerges between mid-April and early June (Stoller and Wax, 1973).

Germination and emergence of weed seeds are governed by the interaction of environmental conditions and seed dormancy (Egley, 1986). Roberts and Potter (1980) reported that initial seedling emergence of weeds is governed by a temperature threshold so that when soil temperatures reach a specific level, seedling emergence begins if moisture is available. Forcella et al. (1997) reported that weeds exhibit an upper temperature threshold also, which induces seed into dormancy, whereas Egley (1986) found that amplitude of daily temperature fluctuation most accurately described the temperature threshold for seedling emergence.

MANAGEMENT STRATEGIES RELATED TO SEEDLING EMERGENCE

Because weeds have a characteristic emergence pattern, weed densities in-crop can be altered by a crop’s planting date. One strategy is to delay planting of the crop, which allows producers to control weed seedlings before the crop is planted. Effectiveness of this approach, however, has been inconsistent (Wicks 1984), and yields are usually decreased when crops are planted outside their optimum planting date range (Cook and Veseth, 1991).

A more favorable strategy is to rotate crops with different optimum planting dates, which can aid weed management without negatively impacting crop yield. An example of this approach occurs in the semiarid Great Plains of the USA. One rotation used in this region is winter wheat-oilseed crop-fallow, with the oilseed crop being either safflower and sunflower. Normal planting dates vary between these crops; safflower is planted in early April whereas sunflower is planted in early June.

The oilseed crop grown dramatically affects weed densities in the crop; the explanation for this trend is related to weed emergence. The region’s weed community displays two peak periods of emergence (Fig. 7–5); the first peak represents cool-season weeds whereas warm-season weeds emerge during the second peak in late May and early June (Anderson, 1994). When safflower is planted, over 70% of total weed seedlings will emerge within 10 wk of planting (Fig. 7–5). However, if sunflower is grown, more than 80% of weed seedlings will emerge before planting, and thus, can be easily controlled. This trend shows that rotating crops with different growing seasons can reduce weed densities in-crop by as much as 80%.

Another strategy to reduce seedling emergence is maintaining plant mulch on the soil surface. In semiarid regions, residue from a winter wheat crop reduced
seedling emergence 70% and weed biomass 45% in the following corn crop, if residue levels exceeded 3400 kg ha$^{-1}$ (Crutchfield et al., 1986; Wicks et al., 1994). In humid regions, a similar reduction in seedling emergence can be obtained with cover crops such as rye (*Secale cereale* L.) or hairy vetch (*Vicia villosa* Roth) (Teasdale, 1996). The cover crop is usually established in the fall and produces biomass in early spring. Herbicides or tillage control the cover crop, with a summer annual crop planted into the cover crop residue. Plant mulch suppresses weed germination and emergence by altering environmental conditions affecting germination, physically impeding seedling growth, or inhibiting germination and growth by allelopathy (Crutchfield et al., 1986; Teasdale, 1996).

No-till systems also affect seedling emergence, but this effect varies between climatic regions. In humid regions, weed densities are higher in no-till systems compared to systems with moldboard plowing (Koskinen and McWhorter, 1986; Froud-Williams, 1988). This trend occurs because of species shifts in the weed community to small-seeded species and perennial weeds which are adapted to nondisturbed conditions. In semiarid regions, however, tillage impacts weed emergence differently; seedling densities are reduced 35 to 50% in no-till systems compared to tillage with a sweep plow$^1$ (Anderson, 1999). The sweep plow, with its shallow mixing of soil, places weed seed in more favorable sites for germination, hence, increasing seedling emergence compared to seeds remaining on the soil surface in no-till.

$^1$A sweep plow is comprised of V-shaped blades 75-cm wide and severs weed roots with minimum soil disturbance, tilling to a depth of 5 to 8 cm.
These conflicting trends suggest that generalizations about tillage impact on weed densities are tenuous because of confounding interactions among tillage, implement, crop sequencing, environment, and weed species. An example of this complex interaction occurred in a semiarid rotation study where densities of foxtail \((\text{Setaria} \text{ spp.})\) responded differently to tillage in two rotations (Anderson et al., 1998). Foxtail density was eightfold less in no-till compared to conventional-till (sweep plow and disk tillage) in a spring wheat–fallow rotation, contrasting with foxtail density in a spring wheat–winter wheat–sunflower rotation, which was 12-fold greater in no-till.

**Interference**

Weeds interfere with crop growth by competing for resources such as water, light, and nutrients. Interference is related to factors such as weed density, time of interference, and weed species. The relationship between crop yield loss and weed density is best described with a rectangular hyperbola model (Cousens, 1985). With this relationship, impact of low weed densities on crop yield follows a linear relationship; at higher densities, weeds began competing with each other, thus the competitive effect per unit of weed density decreases.

A second factor of interference is how weed growth coincides with crop growth. Weeds that emerge simultaneously with the crop are more competitive than if weeds emerge after the crop (O’Donovan et al., 1985). Time of interference relationships vary with crop, weed species, and environmental conditions, but consistently, a plant, whether a crop or a weed, that occupies a space first gains an advantage in resource capture (Mortimer, 1984). Interference is also affected by species involved. White and Coble (1997) found that competitiveness among weed species varied 10-fold, whereas crops also differ in competitiveness with weeds; crops grown in rows 15- to 30-cm wide are more competitive than crops grown in rows 75- to 100-cm wide (Patriquin, 1988).

**MANAGEMENT STRATEGIES RELATED TO INTERFERENCE**

Strategies that reduce or delay weed seedling emergence, such as plant mulches, favor crops over weeds. The magnitude of this trend was demonstrated by O’Donovan et al. (1985), who found that wheat or barley’s tolerance to wild oat interference increased 3% for each day of difference between crop and wild oat emergence.

Additionally, crop tolerance of weed interference can be enhance by improving crop vigor and early season growth (Mortimer, 1984). One strategy that improves crop vigor is diverse crop rotations; rotating crops can improve crop growth and grain yield 15 to 30% (Crookston et al., 1991; Anderson, 1998a). Second, cultural practices in-crop can improve crop tolerance to weeds. For example, banding N fertilizer with barley seed at planting reduced green foxtail density and interference compared with N-applied broadcast (O’Donovan et al., 1997). Barley’s access to the banded N favored its early season growth and competitiveness with weeds. Other cultural strategies that increase crop tolerance to
weeds include taller cultivars, higher seeding rates, and narrower row spacing (Challaiah et al., 1986; Carlson and Hill, 1985).

Crop tolerance to weed interference can be further enhanced by a cultural system approach, where several cultural practices are combined into a system. At a semiarid site in the USA, corn yield loss due to grass (*Setaria* spp.) interference was 43% when corn was planted at 37 000 plants ha\(^{-1}\) in rows 76-cm wide with N fertilizer applied broadcast (conventional system in Fig. 7–6). Impact of a single cultural practice, such as N banding, narrower row spacing, or increased crop density, was minimal in reducing yield loss. However, when these three practices were combined into a cultural system, yield loss was only 13%; a four- to fivefold difference in yield loss compared to a single cultural practice (Anderson, 2000b). This study showed that combinations of cultural practices can synergistically improve crop tolerance to weeds. Cultural systems are similarly successful with other crops, such as sunflower, proso millet, and winter wheat, provided that at least three cultural practices comprise the system (Anderson, 1997, 2000a). Production systems can favor synergism among cultural strategies even more by

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**Fig. 7–6.** Corn grain yield in weed-free and weed-infested conditions as affected by cultural practice combinations. Conventional system was 37 000 plants ha\(^{-1}\) at a row spacing of 76 cm, with N fertilizer broadcast at planting. Cultural practices were banding N by the seed, increasing crop density to 47 000 plants ha\(^{-1}\), and reducing row spacing to 38 cm. Study conducted at a semiarid site, Akron, CO, with data averaged across 3 yr. Foxtail millet (*Setaria italica* L.) was used as an indicator weed species infesting corn. Bars with the same letter are not significantly different based on Fisher’s LSD (0.05) (adapted from Anderson, 2000b).
integrating rotational effects on crop vigor with cultural systems, further enhancing crop tolerance to weed interference.

Reproduction

Seed production by weeds present in crops is the main source of weed seeds for the seed bank (Roberts, 1981). Number of seeds per plant can be surprisingly high; ranging from 250 seeds per plant for wild oat to 100 000 seeds per redroot pigweed plant (Stevens, 1932).

Seed production is affected by a weed’s interaction with the crop. If a crop gains a competitive advantage over a weed, seed production can be drastically reduced. For example, wooly cupgrass \([Eriochloa villosa (Thunb.) Kunth]\) seed production was reduced more than 95% if seedlings emerged when corn had five leaves, compared with seedlings emerging simultaneously with corn (Mickelson and Harvey, 2000). Similarly, jointed goatgrass seed production was reduced 80% if seedlings emerged 6 wk after winter wheat (Anderson, 1993). Crops also vary in competitiveness with weeds. Proso millet and corn are summer annual grass crops with similar growth periods. Proso, planted in 20-cm row spacing, reduced weed growth and subsequent seed production 10-fold compared to corn, which was grown in 76-cm row spacing (Anderson, 1999).

MANAGEMENT STRATEGIES RELATED TO REPRODUCTION

The cultural systems approach that increases crop tolerance to weed interference also improves crop competitiveness with weeds, which consequently reduces weed seed production. Jointed goatgrass and feral rye (\(Secale\) spp.) are difficult-to-control weeds in winter wheat; successful control relies on reducing seed densities in the soil seed bank. A cultural system comprised of a tall cultivar, increased seeding rate, and nitrogen (N) placement, reduced seed production of these weeds 40 to 45%; a sixfold increase compared to any single cultural practice (Anderson, 1997). This approach, when combined with natural decline of viable seeds in soil achieved with extended rotations (Fig. 7–3b), can reduce weed densities in future wheat 85 to 95% (Anderson, 1998b).

Crop choice also can impact weed seed production. In Argentina, wild oat infest both spring wheat and barley. However, wild oat seed production in barley was one-half the production in spring wheat (Scursoni et al., 1999). This difference was attributed to the later harvesting of spring wheat, which allows more wild oat seed to reach physiological maturity before cutting at harvest. Thus, rotating barley and wheat would aid wild oat population management compared to continuous wheat.

In Australia, Pandley and Medd (1990) developed a “seed-kill” strategy to minimize wild oat \(Avena fatua\) and \(A. ludoviciana\) seed production in winter wheat. Postemergence herbicides are applied at reduced rates to wild oat during its seed development. This tactic stops development of seed viability, thus reducing seed production by wild oat. The “seed-kill” tactic did not improve wheat grain yield; yet, its impact on long-term population trends of wild oat was greater than conventional herbicide treatments applied at winter wheat planting.
Seed Rain

Seed rain occurs with the natural shedding (shattering) of seed by plants in the field, with rate of shattering increasing with plant maturity. After seeds fall to the soil, their survival is related to position on or in soil, which is determined by tillage practices. Longest survival of weed seed occurs when deep tillage such as plowing buries seed 10 cm or more in soil (Aldrich, 1984; Froud-Williams et al., 1984); burial in soil protects seeds from environmental extremes.

Seed rain also is affected by crop harvest, as mechanical harvesting with a combine increases seed shattering. Weed seed entering the combine may be removed with crop seed, however, the majority of weed seeds entering the combine are dispersed throughout the field with chaff and crop residue (Petzold, 1956).

MANAGEMENT STRATEGIES RELATED TO SEED RAIN

Leaving weed seed on the soil surface, such as occurs with no-till systems, can lead to extensive loss of seed viability (Sagar and Mortimer, 1976). A study in England compared winter survival of wild oat seed left on the soil surface to seed buried 2 to 5 cm in soil. Viability of seed on the soil surface declined to <10% after 5 mo; in contrast, more than 50% of wild oat seeds buried in soil were still viable (Fig. 7–7). Loss of seed viability on the soil surface was attributed to environmental extremes (Sagar and Mortimer, 1976). Similar results occurred in New Zealand (Popay et al., 1994), Canada (Thomas et al., 1986), and the USA (Egley and Williams, 1990), where loss of seed viability was greatest on the soil surface.

![Seed Placement](image)

Fig. 7–7. Loss of seed viability of wild oat on the soil surface compared to buried in soil. Study established in October and monitored over winter (adapted from Sagar and Mortimer, 1976).
Froud-Williams et al. (1984) hypothesized that tilling soil shallowly to bury weed seed would enhance seed bank decline, due to greater weed germination. Egley and Williams (1990), testing this hypothesis, suggested leaving weed seeds on the soil surface over winter, then tilling shallowly in early spring to favor germination before planting a crop. However, shallow tillage did not enhance long-term (5 yr) seed bank decline compared to a no-till system.

Dispersal of seed at harvest is a key component in long-term weed population growth (Maxwell and Ghersa, 1992). Woolcock and Cousens (2000) evaluated impact of combine dispersal on *Avena* spp. and *Bromus* spp. population growth in Australia. Combine dispersal increased rate of spread by these species 16-fold compared to a system where seed dispersal at harvest was prevented. They found that a weed’s rate of spread in a field was more dependent on dispersal than on demographic factors. In production fields, weeds commonly are aggregated in patches (Donald and Zimdahl, 1987; Johnson et al., 1996). Harvesting weed patches separately from weed-free sections of a field and cleaning the combine to remove weed seed would minimize seed dispersal and subsequent population growth of weeds over years.

**Summary (Weed Management)**

Cultural strategies can be effective in managing weed population densities. A striking example is the impact of rotation design on weed growth; weed biomass differed sixfold between a rotation comprised of crops with diverse growing periods compared to a monoculture (Fig. 7-4). This impact of rotation design can be further enhanced by other strategies, such as plant mulches, which can reduce weed emergence in crops 50 to 70%. Reducing weed densities and improving crop vigor not only improves herbicide efficacy (Hoffman and Lavy, 1978; Dieleman et al., 1999), but increases options for alternative control tactics (Pedigo 1995).

Furthermore, a systematic integration of various tactics can synergistically improve cultural weed management. An example of this approach was demonstrated with proso millet grown in a semiarid climate (Anderson, 2000a). A production system for proso was designed to disrupt ecological trends of redroot pigweed, thus minimizing its density and interference with proso. One component of the system was not tilling between winter wheat harvest and planting proso to favor weed seed decline over-winter as well as less seedling emergence the following spring. Other components related to proso’s canopy, such as increased seeding rate, taller cultivar, N placement, and delayed planting, improved proso competitiveness with pigweed. The ecologically-based system eliminated yield loss due to weed interference, whereas pigweed interference reduced yield 29% in the conventional system used by producers. Furthermore, seed production by pigweed was reduced 150-fold in the ecological system.

Another example of a successful integration of ecologically-based weed management occurred in Australia. Pandley and Medd (1990), evaluating population dynamics of wild oat in winter wheat with simulation models, suggested that seed demographics of wild oat had the greatest impact on future weed densities. To test this hypothesis, a cultural system comprised of wild oat “seed kill”
during the crop season combined with rotations including summer annual crops was compared to the conventional system of winter wheat-fallow with prophylactic treatments for wild oat control. The ecologically-based system designed to manage wild oat population yielded a threefold economic benefit compared to the conventional system, when projected over a 15-yr period (Jones and Medd, 1997). These examples demonstrate that production systems integrating ecologically-based management strategies with diverse rotations can be successful both in minimizing weed impact on crop growth and improving economic return.

**PEST MANAGEMENT SUMMARY**

Ecologically-based pest management offers numerous alternative opportunities to manage pests, especially if integrated with diverse crop rotations. This approach enables producers to diversify their pest management tactics beyond pesticide use, thus expanding options for producers to manage input costs and pesticide resistance. For example, rotations comprised of both winter and summer annual crops reduce equilibrium weed density (Anderson 1998a), whereas reducing the frequency of a crop within a rotation minimizes the impact of plant diseases on each crop (Bailey, 1996). Rotations designed to emphasize both of these principles will consequently improve crop competitiveness with pests, as greater crop growth and lower weed density will favor natural weed suppression. Thus, designing rotations based on ecological principles will enable producers to pursue alternative pest control tactics, rather than rely solely on pesticides.

A concern with alternative pest management systems is that without maximum control of pests, serious yield and economic losses will occur. Yet, long-term system studies evaluating producer practices show favorable returns with alternative systems. In England, a system based on diverse rotations and ecologically-based pest management was compared to current crop production systems (Jordan et al., 1997). Over a 5-yr period, crop yield with the ecologically-based system was 10 to 20% less. However, production costs were reduced 32%; thus, overall profitability was maintained. Substantial reductions in applied herbicides (26%), fungicides (79%) and insecticides (78%) lowered production costs with the ecologically-based system. A similar study in The Netherlands compared performance of conventional and ecologically-based systems over a 15-yr period (Lewis et al., 1997). Pesticide use was reduced eightfold by implementing alternative practices based on ecological principles. Yields were lower with the alternative systems, yet reduced input costs led to similar net returns.

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Paying special attention to the importance of integrated pest management, the authors emphasize the role of crop rotation and the use of cultural practices in the control of pests and diseases. They highlight the significance of understanding the ecology of pests, particularly in the context of herbicide resistance and the development of new management strategies for wheat and barley in the Great Plains region. The text also underscores the importance of ecological considerations in the development of pest management systems, emphasizing the need for a holistic approach that includes the spatial and temporal dynamics of weed populations in response to changes in crop management practices.

Chapters dedicated to specific pests include discussions on the identification, life cycles, and control tactics for mites, aphids, and other key pests, along with case studies and practical examples from across the United States. The authors also provide insights into the impact of climate change on pest distributions and the need for adaptive pest management strategies.

The book concludes with a comprehensive review of the state of integrated pest management and its future directions, emphasizing the role of interdisciplinary collaboration and the importance of ongoing research to address emerging pest and disease challenges. It is a valuable resource for students, researchers, and practitioners in the field of agricultural pest management.
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