Principles of Biological Weed Control with Microorganisms

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INTRODUCTION

Throughout the world, weeds contribute significantly to reduced crop yield and quality even though management programs to control them with chemical herbicides have been used (LeBaron, 1990; Swanton et al., 1993; TeBeest et al., 1992). In Canada, average annual yield losses due to weeds in 58 commodities were \$984 million, with losses in fruits and vegetables reported to be more than \$80 million (Swanton et al., 1993). Yield losses caused by weeds in the United States were estimated at \$619 million in vegetable crops and \$441 million in fruit and nut crops (Chandler et al., 1984; Charudattan and DeLoach, 1988). Although chemical herbicides are effective against many weeds, the reliance of the agri-food industry on chemicals has led to problems with herbicide-resistant weed populations, reduced soil and water quality, herbicide residues, and detrimental effects on nontarget organisms (Beckie and Morrison, 1993; Heap et al., 1993; Lym and Messersmith, 1988; Neher, 1992; Smith, 1982). An Ontario government initiative entitled Food Systems 2002 proposed to reduce application of all pesticides by 50% through research, education, and infrastructure by the year 2002 (Swanton et al., 1993). Furthermore, environmental concerns have motivated researchers to investigate other weed control measures as alternatives to chemical herbicide control. It has been suggested that the utilization of plant pathogens for biological weed control be used and integrated into weed management systems (Charudattan and DeLoach, 1988; Swanton et al., 1993; TeBeest et al., 1992; Wapshere et al., 1989). Compatibility of microbial herbicides with chemical herbicides has been demonstrated (Grant et al., 1990a, 1990b), and researchers have suggested that it may be possible to improve the efficacy of bioherbicides by applying chemicals at sublethal rates (Charudattan and DeLoach, 1988). Moreover, use of herbicide(s) in combination with biological agents may expand the spectrum of weeds controlled in the field. This paper discusses the various types of biological control, their status and prospects, and how biological weed control may be implemented into weed management systems.

BIOLOGICAL WEED CONTROL

Types of biological weed control

Biological control, by definition, is the use of a biotic agent to suppress or reduce a population of a pest (Baker, 1987; Hoy, 1990; Watson, 1991). Control of weeds using this approach can complement and be integrated with existing cultural and chemical methods of weed control.

The two major types of biological weed control are the classical (or inoculative) approach and the inundative (or bioherbicide) approach (Charudattan, 1991; Hasan and Ayres, 1990; TeBeest et al., 1992; Wapshere et al., 1989; Watson, 1991). The term "mycoherbicide" is used when a fungal pathogen is used as the biological agent (TeBeest et al., 1992). For the purpose of this review, the term bioherbicide will be used to include several types of biological control agents, including fungi and bacteria. Classical biological control relies on the selection and introduction of an agent that, upon release, is self-perpetuating, survives and establishes itself, and provides long-term control of the weed population (Hasan and Ayres, 1990; TeBeest et al., 1992; Wapshere et al., 1989; Watson, 1991). This strategy is mainly used with weeds introduced from another continent or geographical location and involves the importation of one or more of its natural enemies

(insect or pathogen) from where the weed originated. Classical biological control is considered to be an ecological response because the agent reduces the weed population below the socioeconomic or ecological threshold (Hasan and Ayres, 1990; Wapshere et al., 1989; Watson, 1991). The inundative strategy to biological control involves mass-production and application of a host-specific agent at high inoculum levels over a localized area infested with the target weed (Charudattan, 1991; TeBeest et al., 1992; Wapshere et al., 1989). Exotic and indigenous plant pathogens have been used; however, the majority of the biological agents investigated using this strategy have been indigenous pathogens (McRae, 1988). Weed control using this approach is relatively short-term and the biological control agent is not expected to be self-sustaining. Wapshere et al. (1989) considered the inundative method a technological response to weed control because the biocontrol agent could be applied throughout the growing season, at one or more repeated intervals, to improve its effectiveness. For the purpose of this article the focus will be on inundative biological control with specific examples being cited.

For a bioherbicide to be successful, the pathogen must 1) produce abundant and durable inoculum in culture, 2) be target specific, 3) be genetically stable, and 4) be capable of infecting and killing a significant portion of the weed population under a variety of environmental conditions (Charudattan, 1991). In the majority of cases, a fungal pathogen is used and applied annually as a postemergence bioherbicide in a "product form," similar to chemical herbicides. Several advantages for using bioherbicides over chemical herbicides include their use in situations where the weed is closely related to the crop, where selective herbicides are unavailable for controlling a particular weed and where weed populations have become resistant to a chemical herbicide or family of herbicides (Beckie and Morrison, 1993; Chiang et al., 1989; Heap et al., 1993).

Status of bioherbicides

To date, three mycoherbicides have been developed and registered in the United States and another was registered for use in Canada in 1992 (Charudattan, 1991; Greaves and MacQueen, 1992; Makowski and Mortensen, 1992; McRae, 1988; Mortensen, 1988; TeBeest and Templeton, 1985). 'DeVine', the first registered mycoherbicide, is a liquid preparation of chlamydospores of *Phytophthora palmivora* Butler for control of strangler vine [*Morrenia odorata* (H & A) Lindl.] in citrus orchards (Burnett et al., 1974; Charudattan, 1991; TeBeest and Templeton, 1985). The fungus was first isolated from dying strangler vine plants growing in a citrus grove. Up to 96% weed kill has been obtained with this mycoherbicide and control can last at least 2 years postapplication. Abbott Laboratories (Abbott Park, Ill.) has reintroduced 'DeVine' into the U.S. marketplace and will be selling it in 1995 (R. Charudattan, personal communication).

Colletotrichum gloeosporioides (Penz.) Penz. & Sacc. f.sp. *aeschynomene* is a fungal pathogen, registered for use under the name 'Collego', for control of northern jointvetch [*Aeschynomene virginica* (L.) B.S.P.], a leguminous weed in rice (*Oryza sativa* L.) and soybeans (*Glycine max* L.) (TeBeest and Templeton, 1985). 'Collego' is produced as a wettable powder comprised of dried spores with up to 90% to 100% weed control having been achieved following application (Smith, 1986). The pathogen produces anthracnose symptoms, is specific to the weed, and is applied onto the foliage with conventional herbicide sprayers. The product was on the market from 1982 to 1992, but is no longer for sale by Ecogen (Langhorne, Pa.). This is because the market size cannot justify the costs involved in making the necessary changes in the technology to ferment the product. However, the Univ. of Arkansas is negotiating with Ecogen for the return of its license for 'Collego', and will offer the technology to other interested companies (G. Templeton, personal communication).

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Puccinia canaliculata (Schw.) Lagerh. has been registered as a bioherbicide, under the name 'DR. BIOSEDGE' for use in all cropping areas for control of yellow nutsedge (*Cyperus esculentus* L.) (Greaves and MacQueen, 1992). Application of *P. canaliculata* in early spring completely inhibited flowering and reduced yellow nutsedge stand and new tuber formation by 46% and 66%, respectively (Phatak et al., 1983). Beste et al. (1992) reported that urediniospores of the rust applied in mid-June did not reduce the population of yellow nutsedge, but did decrease its tuber biomass by 32%. Although 'DR. BIOSEDGE' is a registered product, it is not available in the marketplace because the rust is an obligate parasite and mass production of the agent is achieved by raising the inoculum only on live plants (R. Charudattan, personal communication).

The first bioherbicide registered in Canada was 'BioMal', a product comprised of fungal spores of *Colletotrichum gloeosporioides* f.sp. *malvae* for control of round-leaved mallow (*Malva pusilla* Sm.) (Makowski, 1987; Mortensen, 1988). The fungus causes sunken lesions on the stems and leaf petioles and a suspension of 2×10^6 spores/mL can give excellent weed control (Mortensen and Makowski, 1990). Unfortunately, a dew period of at least 20 h along with temperatures below 30 °C are required for infection to occur (Makowski, 1993). As with the other bioherbicides, Philom Bios (Saskatoon, Saskatchewan), the industrial partner involved in development of 'BioMal', decided not to manufacture it because of economic considerations. It was determined that it was too expensive to mass-produce and sell the product at a reasonable cost to farmers (K. Mortensen, personal communication).

The fungus *Colletotrichum truncatum* (Schw.) Andrus and Moore has been identified as a promising mycoherbicide for control of hemp sesbania [*Sesbania exaltata* (Rydb.) ex. A.W. Hill] in agronomic crops (*Gossypium* L.) (Boyette, 1991a, 1991b). Although the pathogen is very specific and highly virulent to the weed and can be mass-produced, environmental factors, particularly lack of moisture, limit its bioherbicidal potential. Improvements in formulation of *C. truncatum*, using unrefined corn oil as an adjuvant, significantly improved its activity by reducing the dew period and spray volume requirements (Boyette, 1994).

Alternaria cassiae Jurair and Khan was recognized as a possible biocontrol agent for sicklepod (*Cassia obtusifolia* L.), a weed found in soybean and peanuts (Walker and Boyette, 1985; Walker and Riley, 1982). It has a narrow host-range and causes leaf-blight symptoms to the weed as well as to coffee senna (*Cassia occidentalis* L.) and showy croton (*Crotalaria spectabilis* Roth). It is capable of stunting and causing death in inoculated sicklepod seedlings and, when applied as a postemergence bioherbicide, has provided 60% to 100% weed control (Charudattan et al., 1986; Walker, 1982). At least 8 h of free water at 20 to 30 °C are required for infection and older plants exhibit resistance to the pathogen (Charudattan et al., 1986; Walker, 1982; Walker and Riley, 1982). In regional field trials, significant reductions in sicklepod stands were obtained, and the fungus gave similar or better levels of control than toxaphene (chlorinated camphene, 67% to 69% chlorine), a chemical used for control of the weed in some U.S. states (Charudattan et al., 1986). Registration of this mycoherbicide under the trade name 'CASST' is pending (Bannon, 1988), but because of inconsistent field performance, Mycogen Corp. (San Diego, Calif.), the company owning the rights for 'CASST', is not planning to pursue registration (Powell and Jutsum, 1993). However, it has been demonstrated that improvements in formulation (such as pH, nutrients, and surfactants) resulted in better germination and infection of sicklepod by *A. cassiae*, resulting in increased bioherbicidal activity (Daigle and Cotty, 1991).

Effective biological control of velvetleaf (*Abutilon theophrasti* Medic.) has been relatively successful with *Colletotrichum coccodes* (Wallr.) Hughes (Gotlieb et al., 1987; Wymore et al., 1988). Optimal disease development occurred with a 24-h dew period at 24 °C, although disease will develop at lower temperatures and with shorter dew periods (Wymore et al., 1988). However, if environmental conditions are less than optimum for disease development, velvetleaf plants will continue to grow after defoliation of inoculated leaves have dropped.

Although mainly fungi have been investigated as potential foliar-

applied bioherbicides, a pathogenic strain of *Xanthomonas campestris* pv. *poannua* demonstrated postemergence activity on annual bluegrass (*Poa annua* L.) in bermudagrass [*Cynodon transvaalensis* Burtt-Davy x *C. dactylon* (L.) Pers.] (Johnson, 1994). The author thought that timing and rate of application of the bacterium were critical for providing a level of control that would be suitable to most golf course superintendents. *Pseudomonas syringae* pv. *tagetis* is also being pursued as a possible bioherbicide for Canada thistle (*Cirsium arvense* L.) control in soybean (Johnson et al., 1995). Application of the bacterium in the spring reduced the number of Canada thistle stems/m² by 78%, compared to the controls, with no disease occurring on the soybean.

In the United States and Canada, several projects have focused on deleterious rhizobacteria for biological control of weeds (Begonia et al., 1990; Boyetchko and Mortensen, 1993; Dorworth, 1992; Harris and Stahlman, 1992, 1993; Kennedy et al., 1991, 1995; Kremer, 1987; Kremer et al., 1990; Souissi and Kremer, 1994). These soil microorganisms are often overlooked because visual disease symptoms, such as root discoloration and wilting, are not obvious under field conditions.

Most of the rhizobacteria associated with weed species were found to be fluorescent and other pseudomonads, *Flavobacterium* spp., *Erwinia herbicola*, and *Alcaligenes* spp. (Kremer et al., 1990). Souissi and Kremer (1994) isolated rhizobacteria from leafy spurge (*Euphorbia esula* L.) roots and evaluated their potential for biological control using cell cultures and callus tissues of leafy spurge. Two isolates significantly reduced the viability of cells and affected callus growth. One isolate caused cellular leakage while the other caused browning of callus tissue, leading the authors to conclude that the modes of actions of each isolate may differ because symptoms on callus tissue induced by each of the isolates differed. The method using cell cultures for screening rhizobacteria for biological weed control could provide a labor- and cost-saving measure for evaluation of rhizobacteria as biocontrol agents.

Kennedy et al. (1991) demonstrated that a *Pseudomonas fluorescens*, strain D7, was inhibitory to downy brome (*Bromus tectorum* L.) and capable of reducing populations of the weed in the field. The D7 strain produced metabolic bi-products (i.e., phytotoxic fractions) that caused discoloration of roots and reduced root elongation (Tranel et al., 1993). Partial purification of the phytotoxic fraction revealed a complex of several components that upon further purification resulted in loss of phytotoxicity (Gurusiddaiah et al., 1992, 1994). Because of this instability, it may be more feasible to use the bacterium itself as a delivery system for biological control.

In western Canada, inhibitory rhizobacteria are being investigated as potential biological control agents (Boyetchko and Mortensen, 1993). More than 1000 rhizobacteria isolated from prairie soils have been screened for their inhibitory effects against annual grassy weeds (Boyetchko, 1994; Boyetchko and Mortensen, 1993). Host-range tests with several isolates suppressive to downy brome demonstrated that the effects of the rhizobacteria and their secondary metabolites are host-specific and the amount of reduction in root growth was found to be concentration-dependent (Boyetchko and Holmström-Ruddick, 1995). Results from other researchers have also indicated that the effect of rhizobacteria can be host-specific (Cherrington and Elliott, 1987; Elliott and Lynch, 1985; Kennedy et al., 1991). Tests conducted on nontarget hosts (i.e., spring and winter cereal crops) showed little or no detrimental effects to root and shoot growth and, in some cases, improvements in plant growth occurred, depending on the crop cultivar and rhizobacterial isolate (Boyetchko and Holmström-Ruddick, 1995). In this situation, it may be possible to provide a competitive advantage to the crop by using a rhizobacterial isolate as a deleterious biological weed control agent concomitantly as a plant-growth-promoting rhizobacterium (PGPR) in the crop.

Several rhizobacteria have also exhibited suppressive properties against green foxtail [*Setaria viridis* (L.) Beauv.] and wild oats (*Avena fatua* L.) (Boyetchko, 1994; Boyetchko and Mortensen, 1993). Experiments are currently underway to screen for potential isolates deleterious to these weeds and test their effectiveness using various weed/crop densities. The critical evaluation of these rhizobacteria as biological weed control agents will take place when field trials are

initiated. Various types of delivery systems effective in introducing these soilborne agents in the field are being investigated (H.D. Mooney and S.M. Boyetchko, unpublished data). Targeting the weed seeds and seedlings within the soil profile with these soil microbial inoculants and development of suitable application technology are key issues that must be addressed for rhizobacteria to be used for biological control on a practical scale.

Constraints in biological weed control

There are several constraints that may limit the success of developing and commercializing bioherbicides. Selection of the candidate agent is very complex but preliminary screening programs, a necessary component for development of bioherbicides, involve a single plant system only (i.e., the weed). Their potential will be realized when testing is conducted in combination with the crop and weed under field conditions with various weed densities. Selection of the target weed is also important. Many mycoherbicides are specific to one weed species or group of weeds, thereby restricting their commercial potential to small niche markets (Makowski, 1997). In agroecosystems, a complex of several weed populations exists where biological control strategies may only control one weed. Selection of a target weed that is a major pest may alleviate this problem, provided that control of the minor weeds is more easily accomplished through other means (Charudattan and DeLoach, 1988).

Mycoherbicides generally have a long dew period requirement and specific temperature regime for infection and disease development to occur (Charudattan, 1991; Makowski, 1993; TeBeest et al., 1992). In some instances, at least 12 h of dew period are required (Boyette, 1994; Makowski, 1993; Morin et al., 1990) but this may be overcome by formulating foliar-applied bioherbicides with invert (water-in-oil) emulsions (Connick et al., 1991; Daigle et al., 1990; Daigle and Connick, 1990). Other technological constraints, including mass-production, formulation, shelf life, and the delivery system are limiting technological factors that must be addressed before bioherbicides will be successful at a commercial level (Greaves and MacQueen, 1992). Large-scale production of viable and stable propagules of the biological control agents (e.g., fungal spores, mycelia, bacterial cells) is required, with submerged fermentation being the method most commonly used for mass-production (Auld and Morin, 1995). Solid-substrate fermentation may be another viable option, but this technology may not be available or economically feasible at present. Mass-production has been a limiting factor in the success of introducing some mycoherbicides, such as 'BioMal', into the marketplace (K. Mortensen, personal communication). Developing suitable formulation for bioherbicides is another limiting factor that has received a great deal of attention (Auld and Morin, 1995; Connick et al., 1991a, 1991b; Daigle and Cotty, 1992; Greaves and MacQueen, 1992). Use of invert emulsions, encapsulation of propagules into organic polymers (e.g., sodium alginate), and into a wheat-gluten matrix are being explored and have been discussed in a recent review (Auld and Morin, 1995).

Application of biological control agents with other chemical pesticides, including herbicides, insecticides, and fungicides, may present another obstacle. There may be problems if mycoherbicides are incompatible with chemical pesticides, especially if their viability or efficacy is adversely affected by the chemical (Charudattan, 1991; Hoy, 1990). Phatak (1984) showed that biological control could be integrated into a weed management system. By combining the rust *P. canaliculata* with the herbicide paraquat (1,1'-dimethyl-4,4'-bipyridiniumion), 99% control of nutsedge was obtained compared to 60% control with the rust alone and 10% with paraquat alone. In greenhouse trials, tank mixing the mycoherbicide *C. gloeosporioides* f.sp. *aeschynomene* with the herbicide propanil [*N*-(3,4-dichlorophenyl) propanamide] or with the fungicide benomyl [methyl-1-(butylcarbamoyl)-2-benzimidazolecarbamate] resulted in inhibition of fungal infection of northern jointvetch (Smith, 1986). However, when the mycoherbicide was applied prior to application of the chemical herbicide or fungicide, there was no reduction to disease infection and development. Split applications of some herbicides before or after application with the bioherbicide, 'BioMal', resulted in

enhanced control of round-leaved mallow compared to application of 'BioMal' alone (Grant et al., 1990b). Although some reduction in efficacy of 'BioMal' was observed when combined with several pesticides, more than half the herbicides tested at 0.01 to 2 times the recommended rates did not affect growth of the fungus in vitro (Grant et al., 1990a). These results indicate the potential for using sublethal doses of chemical herbicides to enhance the efficacy of mycoherbicides such as 'BioMal'. Biological control cannot replace chemical pesticides, but researchers generally believe that it would be compatible with other management strategies, including chemical means of pest control. Smith (1986) suggested that it should also be possible to develop new strains of biocontrol agents such as *C. gloeosporioides* f.sp. *aeschynomene* that are resistant to various chemical pesticides to reduce the negative impact that pesticides may have on biological weed control agents.

WEED ECOLOGY AND BIOLOGICAL CONTROL

Although no single weed control method can be expected to provide complete control, it is likely that biological control will be used as an element of an integrated weed management (IWM) system, rather than as a replacement for chemical herbicides (Swanton and Weise, 1991; Wapshere et al., 1989). When evaluating weed competition, information on critical period and time of emergence are major considerations (Aldrich, 1987; O'Donovan et al., 1985; Swanton and Weise, 1991; Weaver, 1984). Critical period is the minimum time that weeds must be suppressed to prevent crop yield losses (Weaver, 1984). The two components to critical period are 1) the length of time control of weeds is necessary to prevent crop yield losses, and 2) the length of time a crop will tolerate weeds before the weed interferes with crop growth and thus, reduces crop yield (Swanton and Weise, 1991; Weaver, 1984). Knowledge of the duration of the critical period, which varies with the weed species and density, crop (and variety), year, and location, would aid in determining timing of application and optimum dose of a herbicide. Relative time of emergence of a weed will also influence weed competition (Aldrich, 1987; O'Donovan et al., 1985). A plant species that germinates early in the season has a competitive advantage over later germinating plant species whereby it competes for resources (i.e., soil moisture, nutrients, and light) and becomes better established (O'Donovan et al., 1985). Furthermore, relative time of emergence of weeds with respect to the crop would affect the severity of yield loss.

For biological control to be a viable option for weed management, the critical period and relative time of emergence should be considered. They provide useful information on the period of time required for a bioherbicide candidate to control the weed before there are yield reductions, and could provide a basis for deciding whether the bioherbicide will be effective for controlling a weed population within a particular crop. If the biological control agent takes too long to kill or suppress the weed, then it may be difficult to justify using it as a weed control measure. This difficulty may apply especially to crops that have little or no tolerance for weeds early in the growing season. If a particular weed targeted for biological control is an early germinator, compared to the crop, selection of type of biological weed control agent will be critical. While many foliar-applied fungal pathogens lend themselves to postemergence application, soilborne agents (fungi and rhizobacteria) may be used as preemergence biocontrol agents. Therefore, it may be preferable to select for a preemergence type of biocontrol agent rather than a postemergence agent if the targeted weed germinates early in spring and is a good competitor for resources.

One major constraint of many foliar-applied bioherbicides is duration of dew period, since fungal spores may require free moisture to germinate (Fernando et al., 1994). Early season weed control is necessary to ensure that the weed does not out-compete the crop; therefore, a fast-acting bioherbicide is desired to reduce weed competition and, subsequently, crop yield losses. Efficacy of *C. coccodes* to control velvetleaf was improved when phylloplane *Pseudomonas* spp. were co-inoculated with the fungus, resulting in the development of disease symptoms 4 to 5 days earlier compared to plants treated with *C. coccodes* alone (Fernando et al., 1994). Therefore, reducing the time required for the biological control agent to effectively suppress

growth of the weed could reduce the competitive ability of velvetleaf.

Research investigating the efficacy of *A. cassiae* under field conditions showed that competition by sicklepod in soybean could be reduced (Walker and Boyette, 1985). Multiple applications of the bioherbicide resulted in yield increases in soybean,* where three applications produced yields similar to yields from weed-free control plots. Therefore, a biological control agent can exert changes in crop/weed interference, making the crop more competitive. However, farmers may find multiple applications of a biological control agent impractical and particularly expensive. Through formulation, Boyette (1994) was able to reduce the dew period requirement of *C. truncatum* for controlling hemp sesbania and thus improve its bioherbicidal activity. Inclusion of unrefined corn oil in the formulation resulted in a decrease of dew requirement from 12 to 2 h to achieve disease development and death and thus provided earlier suppression of hemp sesbania.

Rhizobacteria have been pursued for biological control of downy brome, a winter annual grassy weed that competes well with winter cereals for space, water, and nutrients (Boyetchko and Mortensen, 1993; Kennedy et al., 1991). Complete eradication of downy brome in winter wheat (*Triticum aestivum* L.) was not achieved using *P. fluorescens* D7 strain as a biological control agent, but reduced competition of the weed in the crop was accompanied by an increase in crop yield by 18% to 35% (Kennedy et al., 1991). In another study, application of deleterious soil bacteria for control of jointed goatgrass (*Aegilops cylindrica* Host.) in winter wheat resulted in reductions in aboveground growth of the weed from 30% to 76% (Kennedy et al., 1995). Yield of winter wheat was either not detrimentally affected or wheat yield increased up to 22% concomitantly with reduced weed competition. Selected rhizobacterial isolates that reduce growth of downy brome and green foxtail were capable of significantly increasing growth of various cereal crops under greenhouse conditions (Boyetchko, 1994; Boyetchko and Holmström-Ruddick, 1995). One isolate reduced shoot and root dry weight of green foxtail by up to 50% while shoot dry weight of spring wheat increased by more than 20% (H.D. Mooney and S.M. Boyetchko, unpublished data). Therefore, it may be possible that complete eradication of the weed is not necessary and that biological control agents may confer an advantage to the crop, allowing it to out-compete the weeds. However, crop/weed interference studies in the field must be conducted to determine if this will occur.

It has been proposed by Kremer (1993) that soil microorganisms associated with weed seeds be utilized in an integrated pest management program. After observing deleterious effects to growth of weed seedlings and viability of weed seeds, researchers have suggested that certain microbes capable of attacking seeds be selected to deplete the weed seed bank (Kennedy et al., 1991; Kremer et al., 1990). Kremer (1993) further suggested that selected bacteria and fungi, capable of producing a variety of microbial toxins that are absorbed into the developing seed embryo before the seedcoat becomes impermeable, be used to manage weeds. By integrating the use of soil microbes and their metabolic by-products with other weed control measures, it could be possible to deplete the soil of weed seeds, particularly dormant, persistent weeds, and provide crops with less competition from weeds.

CONCLUSION

Although chemical herbicides have provided very effective weed control, weeds continue to contribute significantly to crop yield losses. Biological weed control has the potential to be a viable control measure for integration into weed management systems and there are several examples of fungal pathogens available for development as bioherbicides. Exploration with soilborne microbes, such as rhizobacteria, exhibiting weed suppressive properties provides a further source for biological control candidates. Unfortunately, technological and ecological constraints may impede the development of biological control agents. Mass-production, formulation, and effective delivery systems will be key factors for consistent performance of microbials in the field. Environmental factors, such as temperature and dew period requirement, have a tremendous impact on the perfor-

mance of foliar-applied pathogens. These constraints might be overcome through appropriate formulation and development of application technology systems.

Biological control is more likely to be effective when integrated as a component in a weed management system. Knowledge of weed competition and factors, such as critical period and time of emergence, could provide useful information for optimizing the efficacy of a biocontrol agent. Reducing weed competition, thereby providing the crop with a competitive advantage, will be an important feature when evaluating fungi and bacteria for preemergence or postemergence weed control. The ultimate goal is to provide the crop with the type of environment conducive to successful seedling establishment.

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