The Role of Bioherbicides in Weed Management

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ABSTRACT The bioherbicide approach to weed management involves the inundative use of selected microorganisms for attacking specific weeds and controlling their infestations within the same year of application. Ideally, bioherbicides are most effective for weed management in annual cropping systems that are unsuitable for the classical biological control approach, which involve the use of natural enemies requiring more than one year to develop effective, weed suppressive populations. Only a few bioherbicides are successful in field-scale control of weeds while the effectiveness of other candidate bioherbicides has been limited by restricted host-range, elaborate formulation requirements, and lack of persistence in the field. Special situations in which bioherbicides may be most effective include management of weeds that are considered herbicide-resistant, parasitic, and invasive. Based on the current status of bioherbicide use, strategies for widening host ranges, improving formulations for practical use, and improving techniques for enhancement of weed-suppressive activity in conventional and sustainable agricultural systems are needed if bioherbicides are to make significant contributions to non-chemical weed management.

KEY WORDS : Weed biological control, biotic agents, weed-suppressive microorganisms; deleterious rhizobacteria

INTRODUCTION

Biological control of weeds is the intentional use of living organisms (biotic agents) to reduce the vigor, reproductive capacity, density, or impact of weeds (Quimby and Birdsall, 1995). The strategies of biological control can be classified in two broad categories: (i) classical or inoculative, and (ii) inundative or mass exposure. The classical strategy is based on introduction of host-specific organisms (insects, pathogens, nematodes) from the weed's native range into regions where the weed has established and become a widespread problem. The biotic agents, after quarantine to assure host specificity, are released into weed-infested sites and are allowed to adapt and flourish in their new habitat over time to eventually establish a self-perpetuating regulation of the weed infestation at acceptable levels. Thus, classical biological control requires a time period of one to several years to achieve adequate control while the agent population builds up to levels to impact the weed population.

The inundative strategy attempts to overwhelm a weed infestation with massive numbers of a biotic agent in order to attain weed control in the year of release. In contrast to classical biological control, inundation involves timing of agent release to coincide with weed susceptibility to the agent and formulation of the agent to provide rapid attack of the weed host. A development of the inundative

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strategy is the bioherbicide approach, which involves application of weed pathogens in a manner similar to herbicide applications. Since most bioherbicides have been developed using selected plant pathogenic fungi that cause such diseases on weeds as anthracnose and rust, the term mycoherbicide is often used in reference to these fungal preparations.

The objectives of this review are to identify the place for bioherbicides in weed management including their integration into current systems, to develop an understanding of factors affecting their successful use in both conventional and alternative management systems, and to assess the prospects of developing strategies for using bioherbicides in biologically-based weed management.

CURRENT STATUS OF BIOHERBICIDE DEVELOPMENT AND USE

Several selected microorganisms have been extensively evaluated and developed or are under development for commercial application (Table 1). The discovery, development, practical application, and commercialization of early mycoherbicides (i.e., 'Collego', 'Devine', 'Biomal') have been thoroughly described (Charudattan, 1991; TeBeest, 1996). The early mycoherbicides consisted of highly virulent fungal plant pathogens that infected the aerial portions of weed hosts resulting in visible disease symptoms. These fungi could also be mass cultured in artificial media to produce large quantities of inocula needed for field application. Microbial agents comprising more recent bioherbicides can include obligate fungal parasites, soil-borne fungal pathogens, non-phytopathogenic fungi, pathogenic and non-pathogenic bacteria, and nematodes. Many of these organisms have different cultural and application requirements compared to the early mycoherbicides. This presents a curious dilemma in that even though the number of potential bioherbicides and target weeds in diverse habitats has expanded over the past 25 years, the production and formulation requirements and application methods have become more complex. This is a disadvantage for developing production facilities devoted to bioherbicides because standard culturing and processing techniques cannot be used in the preparation of the various biological control agents necessary for attacking several target weeds that typically infest crop production fields. Unfortunately, production systems for bioherbicides, especially mycoherbicides, will continue to follow empirical processes illustrated by evaluation of candidate pathogens on a case-by-case basis (Charudattan, 2001).

The bioherbicides listed in Table 1 include organisms that have been extensively evaluated for commercial development including several that have undergone field testing and evaluation as required by regulatory agencies. The original bioherbicide or mycoherbicide concept was based on mass artificial culture of organisms to obtain large quantities of inoculum for inundative application to the weed host to achieve rapid epidemic buildup and high levels of disease (Charudattan, 1991). Because many of the recent bioherbicide candidates differ from the original definition in requirements for mass production and application, the bioherbicide concept has been re-defined as living products that control specific weeds in agricultural systems within a specific, short timeframe (Hallet, 2005). The following illustrates the diversity of microorganisms currently in use or undergoing testing by describing selected examples of production and application of recent bioherbicides.

Most mycoherbicides consist of fungal pathogens such as the *Colletotrichum* species able to exist saprophytically in the absence of the plant host, which is important in developing artificial culture strategies for production of inocula. However, some fungal pathogens are obligate parasites that can only proliferate directly on host plants. Such is the case of the rust fungus *Puccinia canaliculata*, a foliar pathogen of yellow nutsedge (*Cyperus esculentus*), that is cultured en masse on the weed host planted in small field plots or greenhouses from which uredospores are vacuum-harvested and stored in bulk prior to preparation of the mycoherbicide 'Dr. Biosedge' (Phatak *et al.*, 1983). The harvested uredospores can be applied in the field through center-pivot irrigation systems. The mycoherbicide 'Eco-Clear', containing the fungal pathogen *Chondrostereum purpureum*, must be applied to wounded branches or stumps of weedy tree species to inhibit re-sprouting by enhancing decay of the woody tissues (Prasad, 1996).

Table 1. Examples of microorganisms used in bioherbicides and their target weeds, ecosystems, and current status.

Microorganism	Target weed	Ecosystem	Status / Registered Name	Representative reference
Foliar/Stem Fungal Pathogens:				
Colletotrichum gloeosporioides aeschynomene	Northern jointvetch (*Aeschynomene viriginica*)	Rice, soybean	Commercialized – 'Collego'	Julien and Griffiths, 1998
Colletotrichum gloeosporioides f.sp. *malvae*	Round-leave mallow (*Malva pusilla*)	Flax, lentils, horticultural crops	Commercialized – 'Biomal', 'Mallet'	Grant *et al.*, 1990
Colletotrichum gloeosporioides f.sp. *cuscutae*	Dodders (*Cuscuta* spp.)	Soybean	Product in use in China – 'Lubao'	Julien and Griffiths, 1998
Colletotrichum gloeosporioides	Hakea (*Hakea sericea*)	Mountain meadows	Commercialized – 'Hakatak' (South Africa)	Charudattan, 2001
Colletotrichum truncatum	Hemp sesbania (*Sesbania exaltata*)	Soybean, cotton, rice	Field evaluation; formulation development – 'Coltru'	Julien and Griffiths, 1998
Colletotrichum coccodes	Velvetleaf (*Abutilon theophrasti*)	Maize, soybean	Field evaluation – 'Velgo'	Wymore *et al.*, 1988
Phytophthora palmivora	Strangler or milkweed vine (*Morrenia odorata*)	Citrus groves	Commercialized – 'DeVine'	Julien and Griffiths, 1998
Alternaria cassiae	Sicklepod (*Cassia obtusifolia*)	Soybean	Formulation development – 'CASST'	Julien and Griffiths, 1998
Alternaria destruens	Dodders	Cranberry	Field evaluation – 'Smolder'	Hopen *et al.*, 1997
Puccinia canaliculata	Yellow nutsedge (*Cyperus esculentus*)	Horticultural crops	Field evaluation – 'Dr. Biosedge'	Phatak *et al.*, 1983
Cercospora rodmanii	Water hyacinth (*Eichornia crassipes*)	Waterways, impoundments	Field evaluation; under commercial development	Julien and Griffiths, 1998
Cephalosporium diospyri	Common persimmon (*Diospyros virginiana*)	Pastures, rangelands	Product available from Noble Foundation, Oklahoma	Watson, 1993
Chondrostereum purpureum	Black cherry (*Prunus serotina*); Red alder	Forest	Commercialized – 'Biochon' (Netherlands);	Prasad, 1996
	(*Alnus rubra*)		'ECO-Clear' (Canada)	
Cylindrobasidium leave	*Acacia* spp.	Forest, rangelands	Commercialized – 'Stumpout' (South Africa)	Charudattan, 2001
Nectria ditissima	Red alder	Forest	Field evaluation – 'PFC-Alderkill' (Canada)	Dorworth, 1995
Soilborne Fungal Pathogens: *Sclerotinia sclerotiorum* and *S. minor*	Dandelion (*Taraxacum officinale*)	Turf	Field evaluation; formulation development	Riddle *et al.*, 1991
Rhizoctonia solani	Leafy spurge (*Euphorbia esula-virgata*)	Rangelands	Field evaluation; formulation development	Caesar *et al.*, 1993
Fusarium solani f. sp. *cucurbitae*	Texas gourd (*Cucurbita texana*)	Cotton, soybean	Field evaluation; formulation development	Weidemann and Templeton, 1988
Fusarium oxysporum f. sp. *erythroxyli*	Coca (*Erythoxylum coca* var. *coca*)	Illicit narcotic crops	Under greenhouse testing and formulation evaluation	Bailey *et al.*, 1998
Non-pathogenic Soilborne Fungi:				
Trichoderma virens	Several	Row and horticultural crops	Formulation evaluation and field testing	Héraux *et al.*, 2005a
Foliar Bacterial Pathogens:				
Xanthomonas campestris pv. *poae*	Annual bluegrass (*Poa annua*)	Turf, athletic fields	Commercialized – 'Camperico' (Japan)	Imaizumi *et al.*, 1997
Pseudomonas syringae pv. *tagetis*	Asteraceae (Composite) weeds	Maize, soybean	Field evaluation; under commercial development	Johnson *et al.*, 1996
P. syringae pv. *phaseolicola*	Kudzu (*Pueraria lobata*)	Non-cropland, pastures	Field testing	Zidack and Backman, 1996
P. syringae strain 3366	Corn spurry (*Spergula arvensis*); Fireweed (*Epilobium angustifolium*)	Cranberry	Greenhouse evaluations of bacterial phytotoxins	Norman *et al.*, 1994
Ralstonia solanacearum	Tropical soda apple (*Solanum viarum*)	Pastures; non-crop land	Field evaluation and formulation development	Charudattan, 2001
Non-pathogenic Bacteria :				
Pseudomonas fluorescens D7	Downy brome (*Bromus tectorum*)	Cereal grain crops	Under commercial development	Kennedy *et al.*, 1991
Pseudomonas spp.	Various	Various	Selection of bacterial mutants overproducing amino acids	Sands *et al.*, 2003
Plant Viruses:				
Tobacco Mild Green Mosaic Virus U2	Tropical soda apple	Pastures; non-crop land	Field evaluation and formulation development	Charudattan, 2001
Plant Parasitic Nematodes:				
Subanguina picridis	Russian knapweed (*Acroptilon repens*)	Rangelands	Field evaluation and formulation development	Caesar-ThonThat *et al.*, 1995

Soilborne fungi have become important bioherbicide candidates because these fungi are applied directly to soils to reduce weed populations through decay of seeds prior to emergence or kill seedlings shortly after emergence (Jones and Hancock, 1990). *Trichoderma virens* inoculated in composted chicken manure significantly reduced broadleaf and grass weeds in horticultural crops (Héraux *et al.*, 2005a). Plant pathogenic bacteria including *Xanthomonas campestris* pv *poannua* (Xcp) and *Pseudomonas syringae* pv *tagetis* (Pst), were developed as bioherbicides for control of annual bluegrass (*Poa annua*) and Asteraceae (composite) weeds, respectively (Johnson *et al*., 1996). The Xcp bioherbicide (‘Camperico’) must be applied by spraying the bacterial suspension while mowing to allow bacterial cells to invade wounded tissue of the grass (Imaizumi *et al.*, 1997). The Pst bioherbicide is prepared with organosilicone surfactant to enhance bacterial infection of leaf and stem tissue and onset of disease.

Deleterious rhizobacteria (DRB) are bacteria that differ from bacterial pathogens based on their non-parasitic nature and ability to aggressively colonize plant roots and suppress plant growth without invading the root tissues (Kremer and Kennedy, 1996; Kremer, 2006). The DRB are under intensive investigation for bioherbicidal potential. *Pseudomonas fluorescens* D7 is a soil-applied DRB bioherbicide formulated as a liquid suspension or encapsulated in clay that effectively suppresses downy brome (*Bromus tectorum*) in cereal grain crops (Kennedy *et al*., 1991). Selected DRB formulated as semolina flour granules suppressed velvetleaf (*Abutilon theophrasti*) seedling growth (Zdor *et al*., 2005) and root growth of leafy spurge (*Euphorbia esula*) established in field infestations (Brinkman *et al*., 1999). Mechanically-transmitted viruses (i.e., Tobacco Mild Green Mosaic Virus), produced on surrogate host plants, harvested, and freeze-dried, are under investigation as bioherbicides of invasive weeds including tropical soda apple (*Solanum viarum*) (Charudattan, 2001). Plant-specific nematodes have been reared and formulated for preliminary evaluation for wide-scale management of the rangeland weed, Russian knapweed (*Acroptilon repens*) (Caesar-Thon That *et al*., 1995).

LIMITING FACTORS OF BIOHERBICIDE ADOPTIONS AND USE

Factors of narrow host range, specific requirements for culturing and formulation to assure biotic agent efficacy, and possible by-products of potent mammalian and avian toxins by some fungal agents have limited commercial development of bioherbicides because of their likely low market potential.

Enhancing Host Range of Bioherbicides

Successful incorporation of bioherbicides into conventional agriculture will only be achieved if they are able to effectively and consistently suppress multiple weeds of economic importance on a very large scale (Charudattan, 1990). Currently, the use of a bioherbicide to control one species in a mixture of weeds in the field is questionable if a producer has the option of a broad-spectrum herbicide to control multiple weed species. Fungal pathogens of the same species containing strains or subspecies with activity against several weeds might be developed through selective screening or through genetic recombination or hybridization into broad host-range pathotypes for use against multiple weed targets (Charudattan, 1990; Sands and Pilgeram, 2001). These are long-term tactics, however, as intense evaluation will be required to meet stringent regulations before approval is granted for release of genetically-altered organisms into the environment.

Alternatives to genetic manipulation for improving the spectrum of weeds controlled include using a “multiple-pathogen strategy” and manipulating the formulation to aid infectiveness of the pathogen (Charudattan, 2001). For example, a mixture of three pathogens, *Drechslera gigantia, Exserohilum longirostratum*, and *Exserohilum rostratum*, which were isolated from three different host weeds, successfully suppressed growth of seven weeds of citrus groves in Florida (Chandramohan and Charudattan, 2003). The multiple-pathogen strategy also shows promise for controlling weeds in row crops illustrated by the successful control of eight weedy *Amaranthus* species in soybean by a mixture of *Phomopsis amananthicola* and *Microsphaeropsis amaranthi* conidial suspensions (Ortiz-Ribbing and Williams, 2006).

Screening trials of the bacterial pathogen Pst prepared as a post-emergence bioherbicide revealed efficacy on several economically important weeds in the Asteraceae family including wild sunflower (*Helianthus* spp.), common cocklebur (*Xanthium strumarium*), common ragweed (*Ambrosia artimisifolia*), and Canada thistle (*Cirsium arvense*) in soybean field trials (Johnson *et al*., 1996). Amendment of Pst aqueous suspensions with surfactants to aid the bacteria to efficiently invade plant leaves broadens the host range when it was found that weeds outside the Asteraceae family, green foxtail (*Setaria viridis*), and velvetleaf (*Abutilon theophrasti*), were also severely injured.

Formulation of Bioherbicides

Many of the foliar and stem fungal pathogens require specific levels of humidity (dew periods) and temperature for full effectiveness, which necessitates development of special formulations to assure effectiveness after delivery of the agent in the field. Boyetchko *et al*. (1998) outlined the factors that must be addressed in bioherbicide formulation technology in order to maintain or enhance efficacy of the biocontrol agent as well as to be compatible with conventional field application systems. The main types of formulations currently in use include various emulsions, organosilicone surfactants, hydrophilic polymers, and alginate-, starch-, or cellulose encapsulated granules, all of which have advantages and disadvantages in promoting virulence and efficacy of the biotic agents and ease of application (Charudattan, 2001; Hallett, 2005). The primary functions of the formulation should include predisposal of the weed to infection by the pathogen and protection of the infecting pathogen against environmental constraints while promoting disease development (Charudattan, 2001).

Potential Health Risks of Bioherbicides

Some mycoherbicides exhibit strong herbicidal activity against a range of economically important weeds, however, the fungal pathogens may also produce undesirable mammalian and avian toxins. *Myrothecium verrucaria* is highly effective in controlling a number of weeds through production of herbicidal metabolites during infection of the host plant; however, mammalian-toxic macrocyclic tricothecenes are simultaneously produced, thereby presenting a human health hazard (Anderson and Hallet, 2005). Similarly, tricothecenes are produced by the fungal pathogen *Fusarium tumidum*, under study as a potential bioherbicide for gorse (*Ulex europaeus*) and broom (*Cytisus scoparius*) in New Zealand (Morin *et al*., 2000). Hallet (2005) suggests that fungal pathogens that produce both herbicidal metabolites and mammalian toxins must be fully investigated to assess their role and risks as potential bioherbicides.

BIOHERBICIDES IN CONVENTIONAL CROPPING SYSTEMS

Conventional cropping systems are characterized as large-scale production enterprises that utilize high-yielding crop varieties generally in monoculture or short term rotations planted on the most fertile, productive soils available with large, costly inputs of chemical fertilizers and pesticides. The introduction and rapid adoption of genetically-modified (GM) varieties of the major crops (soybean, maize, cotton, canola) that are resistant to herbicides allow control of a broad spectrum of weeds with a single herbicide. Conventional cropping systems using either GM or non-GM crop varieties are based on the seasonal use of herbicides to reduce weed infestations to acceptable levels so that crops can be grown profitably with little consideration of a more long-term approach for weed management. Despite the advancements in herbicide technology and development of GM herbicide-resistant crops, surveys continue to indicate that farmers perceive annual and perennial weed infestations as the most serious crop pest problem that affect their enterprises (Aref and Pike, 1998; Gibson *et al*., 2005). These findings suggest that many farmers might consider incorporating alternative, effective, nonchemical weed control methods into their overall weed management plans.

Despite limitations of current bioherbicides, chemical herbicide use will level off and possibly decrease in importance due to social and environmental concerns, development of herbicide-resistant weed biotypes, and reduced availability of new, environmentally compatible herbicides while emphasis on “biologically-based pest management” will increase. Bioherbicides may be effective in conventional cropping systems under several circumstances including: (i) weeds evolved resistance to a broad-spectrum herbicide; (ii) excessive rates of herbicides are required to control one weed species (bioherbicides would allow less herbicide use); (iii) parasitic weeds are not controlled due to lack of selective herbicides; (iv) herbicides cannot be used due to cost or environmental limitations; and (v) invasive weed species become established and few herbicide options are available (Kremer, 2002).

Bioherbicides and Herbicide-resistant Weeds

Although management of the multiple-weed complex in row crops may be addressed in the short term through use of herbicide-resistant transgenic crops, herbicide-resistant weed biotypes will eventually develop after repeated applications of the same herbicide in a given field. For example, glyphosate-resistant rigid ryegrass (*Lolium rigidum*) developed after repeated applications of glyphosate in an orchard to control grass weeds (Powles *et al.*, 1998). Even more serious is the development of weed biotypes with resistance to multiple herbicides that are widely used in row crop production. Foes *et al*. (1998) reported a biotype of common waterhemp (*Amaranthus rudis*), a major weed in maize and soybean in the Midwestern U.S., with resistance to two widely-used herbicides. Also, a downy brome biotype was characterized with resistance to eight chemically dissimilar herbicides (Park and Mallory-Smith, 2005). As herbicide resistance becomes more problematic with many common weeds, strategies using bioherbicides will become more important in maintaining adequate weed control in conventional systems. The potential for successful use of bioherbicides in managing herbicide-resistant biotypes was demonstrated where growth of an imazaquin-resistant common cocklebur biotype originating in soybean fields was suppressed with the mycoherbicide, *Alternaria helianthi* (Abbas and Barrentine, 1995).

Bioherbicides and Parasitic Weeds

Many crop production regions throughout the world are infested with parasitic weeds that attack specific crop plants causing drastic yield reduction. There are no selective herbicides for satisfactorily controlling parasitic weeds; therefore, bioherbicides could be potentially highly effective on these weeds. Indeed, some of the most recent successful bioherbicides have been for control of dodders (*Cuscuta* spp.) in soybean and cranberry (Table 1). Also, a soil fungus under evaluation suppresses germination and attachment of witchweed (*Striga* sp.) seedlings to grain sorghum roots, contributing to grain yield increases (Ciotola *et al.*, 1995). Development of this pathogen as a biotic agent could have significant impacts on food production in regions where *Striga* spp. are dominant weed problems. Recently, a strategy for selecting rhizosphere bacteria or fungi that inhibit broomrape (*Orobanche* spp.) germination and infection of horticultural crops by overproducing amino acids has been proposed as an effective bioherbicidal approach (Vurro *et al.*, 2006).

Bioherbicides and Developing Weed Problems

Bioherbicides may also have a place in weed species that have not yet reached a competitive threshold level. An example might be their use against perennial weeds that are increasing under reduced-tillage farming systems. Shifts in weed composition in response to changes in cropping practices, such as tillage, result in development of sub-competitive populations during the early years of the shift. The general tendency is for perennial species to increase as the amount of tillage decreases. For example, common milkweed (*Asclepias syriaca*) infestations increased in the Midwestern United States in response to continued use of reduced tillage. Although common milkweed typically infested wheat, corn, and soybeans under reduced or no-tillage, it probably only slightly reduced crop yields (Aldrich and Kremer, 1997). Bioherbicides might provide a way of keeping this weed from becoming an economically important weed in the future. The discovery of a bacterial disease affecting common milkweed (Flynn and Vidaver, 1995) may lead to the development of the causal agent, *Xanthomonas campestris* pv. *asclepiadis*, as a biotic agent for maintenance of common milkweed infestations below economic threshold levels. The disease is a systemic blight and reduces overall plant vigor and stand density. The report of milkweed bacterial blight is significant because a practical "preventive biological control approach" can be developed and because discovery of similar agents on other perennial weeds for which no options for chemical control is possible.

Bioherbicides may have an important role in managing invasive weeds, defined as those alien plants spreading naturally in natural ecosystems and producing significant changes in terms of composition, structure, or ecosystem processes (Masters and Sheley, 2001). Invasive weeds are an emerging management challenge because from an economic or agricultural productivity perspective most are not undesirable but are considered very disruptive from an ecological and conservation standpoint. Many of the weeds inhabiting rangelands, forests, and riparian areas as listed in Table 1 may be considered invasive weeds. Although classical biological control strategies may be most appropriate for these situations, some bioherbicides developed for weeds in these habitats have shown promise in effective control. The phytopathogenic bacterium *Pseudomonas syringae* pv. *phaseolicola* was shown to suppress growth of the invasive weed kudzu (*Pueraria lobata*) (Zidack and Backman, 1996). Anderson and Gardner (1999) have demonstrated the potential of *Ralstonia solanacearum* as biological control agent of alien kahili ginger (*Hedychium gardnerianum*), and invasive weed in tropical forest ecosystems. Bioherbicides will be of significant value in managing weeds in areas where herbicides are not effective due to regulations that severely restrict or prohibit herbicide use and where a primary management goal is preservation of the environment. These special situations include restoration of native ecosystems, wetlands, national parks, wildlife refuges, and areas bordering waterways (riparian borders). For example, red alder (*Alnus rubra*) is a forest weed that interferes with timber production in the Pacific West forest region of Canada. Red alder infestations can be suppressed using biocontrol fungi that are inoculated into woody stems with injecting devices (Dorworth, 1995). This mycoherbicide is useful for control of red alder along streams, where herbicide application is prohibited, by causing a "slow kill" and allowing simultaneous release of nutrients from dying vegetation for use by desirable tree species as well as gradual re-population of the site by the timber trees.

BIOHERBICIDES IN INTEGRATED WEED MANAGEMENT

An expanded and long-term approach to weed control is integrated weed management in which all available strategies including tillage, cultural practices, herbicides, allelopathy, and biological control are used to reduce the weed seedbank in soil, prevent weed emergence, and minimize competition from weeds growing with desired plants (Aldrich and Kremer, 1997). Like chemical herbicides, bioherbicides may be most effective as a component in an overall management program rather than as a single tactic approach. This may be the most promising situation for bioherbicides as a practical management option in cropping systems. When considered as a three-part system, weed management offers several opportunities for integration of bioherbicides at critical stages during weed development: as seeds in soil, as growing and competitive plants, and during seed production (Aldrich and Kremer, 1997).

Integrating Bioherbicides with Chemical Herbicides

Several scenarios for integrating bioherbicides into weed management programs can be developed (Table 2). Because most biological control agents are specific toward one weed and most production fields contain several predominant weed species, the use of bioherbicides for control of a single species in conjunction with herbicides selected for control of other weeds present is a logical approach. Compatibility of the bioherbicide *Fusarium solani* f. sp. *cucurbitae*, which controls Texas gourd (*Cucurbita texana*), a problem weed in soybean and cotton in the southern United States, demonstrated that it could be integrated into a weed management strategy to broaden the spectrum of weed control within the crop (Weidemann and Templeton, 1988).

Integration with reduced rates of herbicides can successfully improve activity of mycoherbicides toward weeds. For example, *Phoma proboscis* was more effective in controlling field bindweed (*Convolvulus arvensis*) when combined with sub-lethal doses of 2,4-D than when applied alone (Heiny, 1994). Application of either of three herbicides at one-fourth rate with a sub-lethal dose of the pathogen *Pyricularia setariae* achieved complete control of green foxtail, which demonstrated a pathogen-herbicide synergy (Peng and Byer, 2005). The fungus *Colletotrichum gloeosporioides* f. sp. *malvae*, endemic on round-leaved mallow, adequately controls this weed (about 75% kill) when applied alone as a bioherbicide (Grant *et al*., 1990). Several chemical herbicides are only effective on round-leafed mallow in the early seedling stage. Combinations of the bioherbicide with several herbicides at recommended rates were evaluated for post-emergence control at the 4- to 5-leaf stage of growth. Tank mixtures of the fungus with either metribuzin or imazethapyr greatly enhanced control and reduced biomass production over the fungus or the herbicide alone. These results clearly demonstrate that in some cases no single method is adequate for weed control and that combinations of methods are most effective.

Integrating Bioherbicides with Cultural Practices

Cultural practices offer convenient application methods for integrating bioherbicides in cropping systems. Crop rotation is a practice that may also be manipulated to encourage development of specific inhibitory bacteria on roots. Tillage can influence the frequency of inhibitory bacteria occurring in soil and their growth-suppressing activity. Greater proportions of indigenous rhizobacteria inhibitory to downy brome and jointed goatgrass were detected under either conventional or reduced tillage compared to no-till. This finding suggests that application of selected DRB during tillage may be effective in integrated weed management (Kremer and Kennedy, 1996). Vegetative residues at or near the soil surface could serve as substrates for production of weed-suppressive chemicals by DRB applied as bioherbicides directly to the residues. Previous work reporting a rotation effect in corn was due partly to certain rhizobacteria specifically associated with corn roots illustrates the potential for using DRB to achieve suppression of weeds in crop rotation systems (Turco *et al*., 1990). Increasing crop interference in the field by manipulating row spacing, seeding rates and other cultural practices to suppress early weed growth has been proposed as a viable component of integrated weed management (Jordan, 1993). Selection of highly competitive and allelopathic soybean varieties (Rose *et al*., 1984) and matched with compatible bioherbicides may provide early-season weed suppression and require only minimal subsequent post-emergence weed control.

Bioherbicide and Management of Seed Banks and Seedlings

Prevention of seed germination and seedling emergence is fundamental to maximal effective, long-term weed management (Aldrich and Kremer, 1997). Thus, bioherbicides can play a significant role in reducing weed infestations by attacking seeds and seedlings before they become competitive with crop plants. Several approaches for managing the seed bank and seedling emergence have been described including direct application of biotic agents to soil or crop residues (Begonia *et al*., 1998), or to crop seeds to prevent emergence of weeds in the crop seed-germination zone (Kremer, 2000), and in combination with solarization for enhancing seed deterioration in soils (Kremer and Kennedy, 1996). Also, certain agrochemicals that stimulate seed imbibition or germination can be combined with bioherbicides containing selected seed-attacking microorganisms, incorporated into soil, and kill germinating weed seeds (Kremer and Schulte, 1989).

Sustainable Agricultural Systems

Crop production enterprises that avoid or restrict the use of chemical herbicides both in production fields and in environmentally-sensitive areas favor the adoption of bioherbicides. For simplicity, sustainable agriculture encompasses similar systems known as alternative, natural, organic, biological, ecological, and biodynamic farming. The sustainable agricultural systems involve a range of technological and management options to reduce costs, protect health and environmental quality, and enhance beneficial biological interactions and natural processes (National Research Council, 1989). In nearly all cases, little, if any, synthetic chemicals (including herbicides) are used. Thus, sustainable agricultural systems provide the greatest opportunities to study, refine, and implement non-chemical weed management (Liebman and Gallandt, 1997) that will yield valuable information for developing improved bioherbicides and advancing their use in broader biologically-based weed management systems. Because the demand for

Table 2. Strategies for integrating bioherbicides into agroecosystems and assessment of impact on weed management

Strategy	Agroecosystem	Impact	Reference
Combine with herbicide	Row crops; pasture; horticultural crops	Improve control of weeds difficult to control herbicides or bioherbicides	Grant *et al.*, 1990
Apply to herbicide-resistant weeds	Row crops	Reduce potential increase in future herbicide-resistant biotype populations	Abbas and Barrentine, 1995
Combine with tillage	Row crops	Reduce herbicide use; placement in soil	Kremer and Kennedy, 1996
Combine with cover crops, mulches, crop rotation	Row crops; orchards; agroforestry systems	Increase weed control efficacy; reduce herbicide use	Kremer, 2000; Héraux *et al.*, 2005b
Combine bioherbicide with interseeded cover crop	Row, horticulture crops	Improve biocontrol of target weeds (bindweeds)	Pfirter *et al.*, 1997
Apply to crop residues on soil surface weed seed and rhizosphere zones	Row, horticultural crops	Promote proliferation of biotic agents in soil,	Kremer and Kennedy, 1996
Introduce on crop seeds	Row, horticultural crops	Optimize placement of biotic agents for direct attack	Skipper *et al.*, 1996; Kremer, 2000
		on weed seeds and seedlings in soil	
Apply soilborne pathogens, DRB	Row, horticultural, and cereal grain crops	Attack weed seeds and seedlings; reduce seedbank in soil	Begonia *et al.*, 1998
Combine with crop varieties selected for competitiveness, allelopathy	Row, horticultural, and cereal grain crops	Increase weed control efficacy; reduce herbicide use	Kremer and Kennedy, 1996
Combine with plant-growth-regulating chemicals	Row, horticultural, and cereal grain crops	Reduce viable weed seed production, maintain seedbanks at low densities	Kremer and Schulte, 1989
Combine soilborne pathogens with organic soil amendments	Row, horticultural crops	Increase synthesis of phytotoxins, pre-emergence weed control	Héraux *et al.*, 2005a
Crop rotation + residue management + organic amendments	Row, horticultural crops	Develop weed suppressive soils; reduce herbicide use	Kremer and Li, 2003
Combine with solarization	Horticultural crops	Enhance weed seed and seedling elimination	Kremer and Kennedy, 1996
Multiple agents (synergism):			
Bioherbicides + classical agents (i.e., insects)	Pastures, rangelands, forests	Enhance rate of control by classical agents	Caesar, 2003
Bioherbicides + seed-feeding insects	Row, horticultural crops; pastures, rangelands, forests	Enhance reduction of viable seed production; manage weeds escaping early season control	Kremer and Spencer, 1989
Combine different biotic agents	Row, horticultural crops; pastures, rangelands, forests	Enhance weed suppression and widen weed spectrum	Schisler *et al.*, 1991
Combine a suite of biotic agents of same class (i.e., fungal pathogens)	Row, horticultural crops; pastures, rangelands, forests	Enhance weed suppression and widen weed spectrum	Chandramohan and Charudattan, 2003
Combine bioherbicide with resident biotic agents	All systems	Increase bioherbicide efficacy toward weed hosts	Hallet, 2005

bioherbicides for sustainable agriculture and ecosystem management is currently small relative to chemical herbicides, such products may be provided most efficiently through small-scale, specialized industries or even on-farm production facilities focused on “niche markets” (Auld and Morin, 1995; Charudattan, 1990; Hallet, 2005)

Bioherbicides and Biological Weed Management

Bioherbicides may be most effective in managing weeds as a component in a biological weed management system that is associated with sustainable agriculture. Biological weed management involves the use of diversity of biological agents such as bioherbicides and other biopesticides, and biological approaches including allelopathy, crop competition, and other cultural practices to obtain similar dramatic reduction in weed densities often associated with herbicide use (Cardina, 1995). Examples of biological weed management approaches are listed in Table 2. Because some sustainable agricultural systems demand pesticide-free crop production (i.e., organic farming), the approach to weed control resembles a biological weed management system in which bioherbicides are major components. Many of the approaches are similar to those for integrated weed management except that herbicides are not involved. Therefore, bioherbicides that would not be used in conventional integrated weed management because of unacceptable efficacy or too much time required for realization of effects would be under practical use in biological weed management. For example, prevention of weed seed production and reduction of the seed bank could be attained using a bioherbicide consisting of seed pathogens applied to weeds infesting the crop (Medd and Campbell, 1996). However, the impact of the bioherbicide would not be evident for one to two years when noticeable decreases in weed seedling densities occur due to reduced weed seed populations in the soil.

Cover crops and mulches as components of sustainable management systems may be used for integrating bioherbicides by delivering the agents on seeds and promoting their establishment in soils for attack on weed seeds and seedlings prior to planting the main crop. Recent research demonstrated that several cover crop species inoculated with a DRB bioherbicide at planting maintained DRB populations on their roots and in the rhizosphere thereby promoting root colonization of giant foxtail (*Setaria faberi*) seedlings that emerged early in the growing season of the main crop after the cover crops were terminated (Kremer, 2000). Combined effects of the DRB and allelopathic activity of the cover crop residues suppressed the growth of the weeds. Similarly, a “system management” approach where a specific weed growing with a crop is sprayed with a post-emergence bioherbicide and the crop is underseeded with a living green cover crop has resulted in successful control of the target weed as well as the remaining weed flora by the cover crop (Pfirter *et al*., 1997). Also, agents in formulation applied at planting can attack weed seeds and seedlings through delivery of bioherbicides to soil by either direct inoculation of crop seeds or by promoting colonization of crop roots (Skipper *et al*., 1996). Crop roots not only might deliver microbial agents to adjacent weed roots but may also maintain or even enhance the agents’ numbers for attack of seedlings emerging later in the season.

In sustainable agricultural systems the use of synergisms can be explored in which the combined use of two or more methods enable bioherbicides to control weeds more effectively than when used alone (Gressel *et al*., 1996; TeBeest, 1996). Bioherbicide efficacy on hemp sesbania (*Sesbania exaltata*) was increased by combining selected bacteria with the fungal pathogen, *Colletotrichum truncatum* (Schisler *et al*., 1991). Combinations of a *Colletotrichum* sp. bioherbicide with a naturally-occurring rust fungus allowed the bioherbicide to infect the weed host (*Xanthium* sp.) through rust lesions resulting in death of the plant (Morin *et al*., 1993). A seed-feeding insect combined with seed-attacking fungi significantly decreased velvetleaf seed viability and seedling emergence and increase seed infection compared to either the insect or fungus alone (Kremer and Spencer, 1989). Pre-dispersal seed mortality of weeds escaping herbicide control may be effective in manipulating and reducing seed banks in soil. A practical application of soil-applied detrimental bacteria and fungi combined with insects would be in situations where the insect feeds on roots or crowns of target weeds (Caesar, 2003)

The very nature of high inputs of organic amendments and green manure crops in sustainable agricultural systems promotes the ability of crops to compete more vigorously with weeds, which intuitively suggests that efficacy of bioherbicides would also be enhanced when used with these amendments (Gallandt *et al*., 1998). Indeed the bioherbicidal fungus, *Trichoderma virens,* produced the phytotoxin viridiol when grown in organic substrates such as peat and composts making this bioherbicide ideal for use in biological weed management (Jones and Hancock, 1990; Héraux and Weller, 2005a). This bioherbicide combined with herbicidal compounds released by a rye cover crop extended weed suppression throughout the growing season of selected horticultural crops (Héraux *et al*., 2005b). Furthermore, *Trichoderma virens* also produces biocidal compounds effective against fungal plant pathogens, which suggests the possibility of developing biotic agents with efficacy toward multiple pests.

Sustainable agricultural systems are positioned for implementation of novel tactics and approaches for manipulating the field environment to enhance the activity of indigenous pathogens of weeds present as natural bioherbicides. This strategy of weed suppression, also known as "conservation biological control," is an ecological concept that has only recently received attention from an agroecosystems standpoint. Management activities that affect soil organisms can directly affect weeds as demonstrated with reduced tillage, maintenance of high soil organic matter, reduced inputs of agrichemicals, which lead to high populations of deleterious soil microorganisms that contribute to natural weed suppression (Kremer and Li, 2003). Specific examples are limited, however, Lindquist *et al*. (1995) reported a natural population of the fungal pathogen *Verticillium* sp. significantly suppressed velvetleaf growth in soybean under reduced tillage. Additions of composted swine manure to soil inhibited germination and seedling emergence of three weed species possibly by enhancing soilborne weed-suppressive microorganisms (Menalled *et al*., 2005). As pointed out by Hallet (2005), conservation biological control should not be considered the primary weed control strategy but should be investigated as a component of an integrated weed management program.

CONCLUSIONS

Despite apparent advances in biological control as a reliable strategy for weed management, little progress has been made in developing tactics for practical application in agro-ecosystems, especially those involving cropping systems. Efficacious strategies that target multiple weed species are needed. Best success in achieving this may well involve selection of several "core strains" of agents that are adapted to soils and climates in specific regions and are able to suppress growth of weeds comprising the dominant species at that site. To gain acceptance of these strategies, integration of biological control into current management systems is imperative so that the potential effectiveness of the agents can be demonstrated. Bioherbicides targeted for niche markets and their use in sustainable agricultural systems will likely demonstrate the greatest effectiveness in biological weed management in the short term. This will generate impetus for continued discovery and development of bioherbicides for more widespread use. From a weed management standpoint, the integration of multiple tactics, including a diversity of potential bioherbicides and biologically-based approaches, favors the effectiveness and stability required for long-term weed management (Cardina, 1995).

The integration of biological control into current systems also offers augmentative weed control options, as herbicide use becomes more restricted. It is well known that continued use of single herbicide control tactics favors resistance development in certain weed populations and conventional cropping systems. Bioherbicide technology used in appropriate integrated weed management in diversified cropping systems may aid in restoring fertility and productivity to degraded ecosystems and avoid the buildup of herbicide-resistant and invasive weeds. Bioherbicides appropriately integrated in agricultural and environmental restoration systems can play a major role in reclaiming and restoring biodiversity to ecosystems degraded through continuous implementation of conventional cropping systems.

Situations in which environment quality are restored in both ecologically sound farming systems and native habitats will benefit from the use of effective bioherbicides.

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