Integrated Weed Management

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Abstract
The heavy reliance on chemical weed control has become controversial in recent years due to an increase in herbicide resistance and adverse effects on human health, food safety, and the environment. As a result, integrated weed management, the combination of several control strategies (cultural, mechanical, chemical, biological, etc.), has emerged as an economically and environmentally sound solution to managing weed populations. The Convention on Biological Diversity and prominent researchers in the field stress that priority should be given to biological control as a component of integrated pest management. Biological control approaches require, but also provide, detailed insight into weed–crop interactions and how they are influenced by both the biotic and abiotic environments. They can, thus, be viewed as the basis for integrated production but in most cases will require being used in combinations with other weed management tools to achieve acceptable levels of weed control. Various types of integration can be envisaged, of which preventative measures will be most important for developing sustainable agricultural production.

INTRODUCTION

Agrochemical companies promise that transgenic crops will simplify pest management programs through the use of singular chemical tactics. This "silver-bullet" approach has consistently failed and almost certainly will again because of a failure to understand the ecological relationships governing population size and diversity.[1] Furthermore, in many countries, pesticide policies have called for significant use reductions together with the promotion of biodiversity in agro-ecosystems.[2] Initiatives to reduce reliance on herbicides will require a much fuller understanding of how management practices complement one another to maintain weed populations at low equilibrium densities. Biological control approaches require, but also provide, detailed insight into weed–crop interactions and how they are influenced by both the biotic and abiotic environments. They can, thus, be viewed as the basis for integrated production.[3] In most cases, only combinations with other weed management tools will result in acceptable levels of weed control. Various types of integration can be envisaged, of which preventative measures will be most important for developing sustainable agricultural production.

WEED CONTROL, WEED SCIENCE, AND INTEGRATED WEED MANAGEMENT

Agricultural weed management in farming systems is diverging in two distinct directions. In one set of farming systems, farmers rely primarily on herbicides to suppress weeds. This approach is exemplified by the extensive maize (*Zea mays* L.)/soybean [*Glycine max* (L.) Merr.] system of the midwestern United States, where >110 million kg of herbicide active ingredients are applied annually to >95% of the area planted with those two crops.[4] In a second set of farming systems, herbicides are largely or entirely avoided, and weeds are mainly suppressed using physical and ecological tactics. The existence and risk of development of herbicide resistance make herbicide-dependent cropping systems increasingly vulnerable. Moreover, widespread concern about environmental side effects of herbicides, combined with fear for public health, has resulted in several herbicides being banned in some countries and increasing pressure on farmers to reduce their use.[4]

In contrast to the disciplines of plant pathology and entomology, the "how to control" approach was shaped early on in weed science and, until recently, has dominated the discipline. The fact that weeds have been regarded as a problem that can be controlled with herbicides, rather than managed through cropping system design,[5] has resulted in a time lag in developing integrated weed management systems, as compared to integrated pest and disease management systems.[1] The United Nations Conference on Environment and Development (UNCED), in its Agenda 21, recognized integrated pest management (IPM) as the preferred strategy to achieve sustainable agricultural production.[6] IPM typically involves a reduction in the reliance on chemical pesticides, including herbicides.[7] Furthermore, the Convention on Biological Diversity[8] and prominent researchers in the field make the case that biological control should be given priority as a component of future pest management.[9,10]

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Absorbance – Antibiotics

METHODS USED TO CONTROL CROP WEEDS BIOLOGICALLY

Three principal methods of biological weed control can be distinguished (Fig. 1).[3,11] First, the “inoculative” or “classical” approach aims to control naturalized weeds by the introduction of exotic control organisms from the weed’s native range. They are released over only a small area of the total weed infestation and control is achieved gradually. Successful control depends on favorable conditions promoting an increase in the control agent’s population, establishment of epiphytotics, and, thus, reduction of the target weed population. Second, the “inundative” or “bioherbicide” method uses periodic releases of an abundant supply of the control agent over the entire weed population to be controlled. Such biological agents generally are manufactured, formulated, standardized, packaged, and registered like chemical herbicides. Compared to the other two approaches, this approach is characterized by higher application costs and a relatively short time period to achieve a potential control success. Though there have been a number of successful biological control programs against crop weeds with some products resulting in commercial registration (Table 1), bioherbicides have still not managed to occupy a sizable share of the market.[12] This is mainly due to the fact that the reliability of field efficacy has not reached levels comparable with that of chemical herbicides.[13] According to Charudattan,[14] of the bioherbicide projects underway, only 8% of them were successful, leaving 91.5% of the projects uncertain, untried, or ineffective. Thus, it has become increasingly important to prioritize projects with high pathogen aggressiveness, high speed of disease increase, and high rates of population increase, what Charudattan[9] refers to as “killer traits.” Third, and more recently, the “system management approach” of biological weed control had been described.[15,16] It is related to the conservation and augmentative approaches distinguished by some authors. Its aim is to shift the competitive weed–crop relationship in favor of the latter, mainly by stimulating the buildup of a disease epidemic or insect outbreak on the target weed population. The approach excludes the use of exotic organisms (classical approach) and the use of mass amounts of inoculum applied like a herbicide to the whole weed population (bioherbicide approach).

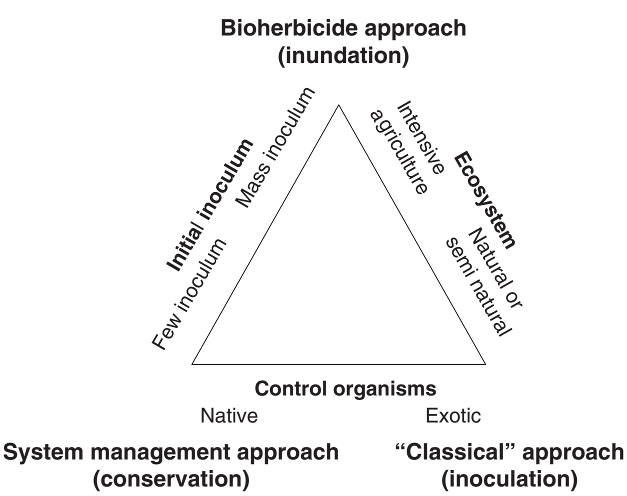

Fig. 1 Schematic diagram showing the three methods of biological weed control in agro-ecosystems (from Ref. [11]) with respect to the initial size of the inoculum released, the origin of the control organisms used, and the ecosystem where the biological control program was implemented. See text for details.

INTEGRATING BIOLOGICAL CONTROL WITH OTHER METHODS OF WEED MANAGEMENT

Weed problems in agro-ecosystems are rarely caused by single weed species. Clearly, biological control, with its inherently narrow species-specific approach, has to be considered as an integrated component of a well-designed pest management strategy, not as a cure by itself. In most cases, combinations of biological agents with other weed management tools will be needed to produce acceptable levels of overall weed control. Such integration can be viewed as a vertical integration of various control tactics against a single weed species, or as a horizontal integration across different weed species in one crop (Table 1).[17] Horizontal integration mainly involves the combination of microbial herbicides with chemical herbicides or mechanical methods to broaden the spectrum of weed species controlled. Furthermore, in situations where particularly high doses of herbicides are needed to control a single weed species while the rest of the weed flora could be controlled by lower amounts, biological control may allow considerable reduction of herbicide inputs and contribute to maintaining species diversity in crops. Three possible types of vertical integration of biological control with other methods of weed management can be distinguished, both in time and space: purpose-specific approaches, ecological integration, and physiological integration (Table 1).[18]

Purpose-Specific Approaches

The type and level of control are chosen according to the context-specific requirements. This often involves different management methods to be applied at different sites. For instance, for a weed that is still spreading, chemical herbicides may well be the method of choice to remove new infestations, while biological control may be relied on to give long-term control of large, established infestations.[43]

Ecological Integration

This term is given to situations where different approaches are used often at the same time on the same infestation. Integration with herbicides[44,45] and with plant (crop)

Table 1 Selected examples of applied integrated weed management involving biological control, and present product status.

Target weed	Common pathogen(s)	Crop/habitat	Type of integration[a]	Type of biological control strategy and status of product	Reference(s)
Northern jointvetch (*Aeschynomene virginica*)	Collego™: *Colletotrichum gloeosporioides* f. sp. *aeschynomene*	Rice and soybean fields	Pathogen–pathogen–herbicide [H] (PSA)	Inundative method Reregistered as Lockdown.	[19]
Stranglervine (*Morrenia odorata*)	DeVine®: *Phytophthora palmivora*	Citrus groves	Pathogen–herbicide [H]	Inundative method Status unknown; EPA issued a Re-registration Eligibility Document (RED) in 2006; it appears that no one has come forward to reregister DeVine.	[20,21]
Velvetleaf (*Abutilon theophrasti*)	*Colletotrichum coccodes*	Corn, soybean	Pathogen–herbicide [H;V/P] (PSA)	Classical method Several organisms are being studied for use as biocontrol agents, though none are currently available for release.	[22,23]
Barnyard grass (*Echinochloa crus-galli*)	*Colletotrichum graminicola*	Various crops	Pathogen–herbicide [V/P]	Classical method Several organisms are being studied for use as biocontrol agents, though none are currently available for release.	[24]
Nutsedges (*Cyperus* spp.)	Dr BioSedge: *Puccinia canaliculata*	Various crops	Pathogen–herbicide [V/P] (PSA)	Inundative method Registered, but commercial development abandoned due to uneconomic production system and resistance in some weed biotypes	[25,26]
Spotted knapweed (*Centaurea maculosa*)	*Cyphocleonus achates*, *Agapeta zoegana*, *Larinus* spp., *Urophora* spp., etc. (see Julien and Griffiths 1998)	Rangeland	Insect–plant competition [V/E] Insect–herbicide [V/P or PS]	Classical method Several organisms are being studied for use as biocontrol agents, though none are currently available for release.	[27–30]
Nodding thistle (*Carduus nutans*)	*Rhinocyllus conicus*, *Trichosirocalus horridus*, *Cassida rubiginosa*	Rangeland	Insect–herbicide [V/P] Insect–plant competition [V/E]	Classical method Several organisms are being studied for use as biocontrol agents, though none are currently available for release.	[31]

(*Continued*)

Table 1 Selected examples of applied integrated weed management involving biological control, and present product status. (*Continued*)

Target weed	Common pathogen(s)	Crop/habitat	Type of integration[a]	Type of biological control strategy and status of product	Reference(s)
St. John's wort (*Hypericum perforatum*)	*Chrysolina hyperici*, *Chrysolina quadrigemina*	Rangeland	Insect–fire [V/E] Insect–plant competition [V/E]	Classical method Several organisms are being studied for use as biocontrol agents, though none are currently available for release.	[32–34]
Water hyacinth (*Eichhornia crassipes*)	*Neochetina eichhorniae*, *Neochetina bruchi*, *Sameodes albiguttalis*	Aquatic	Insect–herbicide [V/P] Insect–pathogen–herbicide [PS]	Classical method Currently, there are no registered bioherbicides, but several candidates have been identified.	[35]
Floating fern (*Salvinia molesta*)	*Cyrtobagous salviniae*	Aquatic	Insect–herbicide [V/PS or P] Insect–fertilizer [V/P]	Classical method Currently, there are no registered bioherbicides, but several candidates have been identified.	[36]
Dyer's woad (*Isatis tinctoria*)	Woad Warrior: *Puccinia thlaspeos*	Farms, rangeland, waste areas, and roadsides	Pathogen (rust)–herbicide [V/P]	Inundative method Registered product. Consists of rust spores on finely ground leaf and stem pieces of infected dyers woad.	[37]
Alders, aspen, and other hardwoods	Chontrol™: *Chondrostereum purpureum*	Rights of way and forests	Pathogen (fungus)–herbicide [V/P]	Inundative method Registered in Canada and the United States and commercially available.	[38–39]
Dandelion (*Taraxacum*)	Sarritor: *Sclerotinia minor*	Lawn and turf	Pathogen (fungus)–herbicide [H;V/P]	Inundative method Registered and commercially available in Canada. U.S. registration is pending.	[40–42]

H, horizontal, V, vertical; P, physiological, PS, purpose specific; PSA, partially sequential application.
[a]See text for details.

competition[46–48] is most widely envisaged. This type of integration essentially summarizes holistic approaches that encompass all modifications to the environment, which may favor the effectiveness of biological control agents and facilitate the management of a weed population.[49]

Physiological Integration

This type of integration exploits synergistic interactions between changes in the biochemistry of weeds, often produced by sublethal effects of herbicides and the effectiveness of biological control agents. Herbicides (or other "synergists") are known to increase incidence of infection and to enhance the growth of pathogens,[50–55] but infection by the pathogen may also facilitate the uptake of herbicides, mainly by injuring the cuticle and epidermis of the host. In addition, various studies have shown greatly increased disease severity and agent effects when combined with phytotoxic metabolites produced by the pathogen[56] or with specific formulation and delivery techniques of microbial herbicides.[57,58] Thus, physiological integration is directed toward combined effects with biological control agents on plant individuals.

Ultimately, optimal management, with minimal disruptive interventions, requires a good understanding of the weed's biology and, especially, population dynamics.[59] Biological weed control requires, and provides, a detailed ex ante analysis of the problem situation, especially of the crop environment, revealing interactions between the various components and their underlying interactions. It should, therefore, be the strategy that is basic to integrated production systems. Bridges between different disciplines need to be built to optimize the fit of biological control into existing management systems.[60–62]

CONCLUSIONS

When weeds are no longer regarded as a problem to be resolved by curative tactics, then prevention becomes the keyword and integrated cropping management becomes the new focus, of which integrated weed management is an important component. Much work remains to be done by scientists spanning a broad range of disciplines in order to be able to integrate soil, crop, and weed management effectively.[63] Further challenges for weed science are the elaboration of effective practices for new crops, new production systems for enlarged farms and fields, and the consequences of climate change. Furthermore, adequate answers need to be found for the increased concern about the conservation of biodiversity and the growing consumer demands on food safety.[64] In parallel, to transfer the scientific knowledge into farming practices, a considerable amount of time must be spent with farmers in order to understand the true practical dimensions of the increasingly complex study systems. In this cropping system design approach, numerous fitness-reducing and mortality events are integrated to manage weed populations, with herbicides being used as a last resort. Prevention involves any aspect of management that favors the crop relative to the weed. This includes the development of competitive crop cultivars, crop rotation, mixed cropping, and allelopathy.[65] Preventative control requires a detailed insight into weed biology and ecology and the ways in which they interact with the crop. Biological control provides a fundamental tool for successful management of weed populations, where weed control no longer considers crop production in a weed-free environment, but instead as a reduction of weed-induced yield losses. By that, it greatly contributes to promoting biodiversity in human-influenced landscapes, a central pillar of modern sustainable agriculture.

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