Principles of Integrated Pest Management with Emphasis on Weeds

Heinz Mueller-Schaerer
University of Fribourg/Pérolles, Fribourg, Switzerland

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. It will do so as a result of fundamental ecological relationships governing population size and diversity.[1] At the same time, in many countries, pesticide policies have called for significant use reductions together with the promotion of biodiversity in agro-ecosystems.[2] However, 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

At the close of the twentieth century, agricultural weed management 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. 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 makes 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 the use of herbicides.[4]

In contrast to disciplines of plant pathology and entomology, the ''how to control'' technological orientation was shaped early on in the evolution of weed science as a discipline and, until recently, this has dominated the science. The fact that weeds have been regarded as a problem that can be controlled with herbicides, rather than managed through cropping system design, 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. IPM typically involves a reduction in the reliance on chemical pesticides, including herbicides. Furthermore, in the Convention on Biological Diversity, the point is clearly made that priority should be given to biological control as a component of future pest management.

METHODS USED TO CONTROL CROP WEEDS BIOLOGICALLY

Three principal methods of biological weed control can be distinguished (Fig. 1)[3,5]: 1) 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 con-

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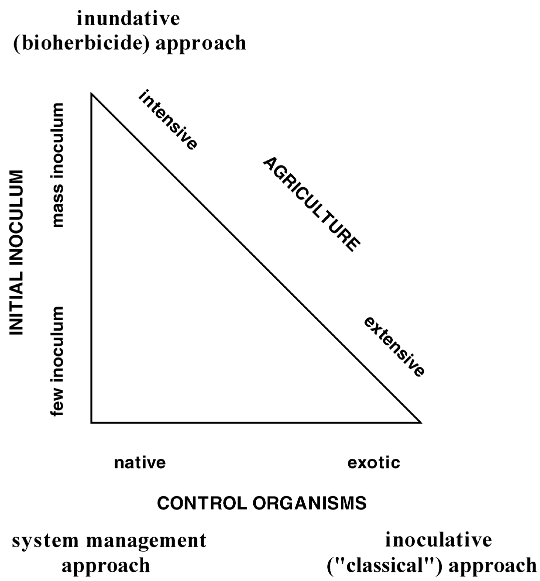

Fig. 1 Methods of biological weed control in agro-ecosystems.

ditions promoting an increase in the control agent's population, establishment of epiphytotics and, so, reduction of the target weed population. 2) 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. 3) More recently, the ''system management approach'' of biological weed control had been described. 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).

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 spectrum, 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[6] (Table 1). 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[7] (Table 1).

Purpose-Specific Approaches

The type and level of control are chosen according to the requirements. This often involves different 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.[11]

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[12,13] and with plant (crop) competition[10,14,15] 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.[16]

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[17–19]

Table 1 Selected examples of successful integrated weed management involving biological control

Target weed	Crop/habitat	Control methods	Type of integration[a]
Northern jointvetch (*Aeschynomene virginica*)	Rice and soybean fields	Pathogen–pathogen–herbicide	Horizontal (PSA[b])
Stanglervine (*Morrenia odorata*)	Citrus groves	Pathogen–herbicide	Horizontal
Velvetleaf (*Abutilon theophrasti*)	Corn, soybean	Pathogen–herbicide	Horizontal; vertical/physiological (PSA)
Barnyard grass (*Echinochloa crus-galli*)	Various crops	Pathogen–herbicide	Vertical/physiological
Nutsedges (*Cyperus* spp.)	Various crops	Pathogen–herbicide	Vertical/physiological (PSA)
Spotted knapweed (*Centaurea maculsa*)	Rangeland	Insect–plant competition	Vertical/ecological
		Insect–herbicide	Vertical/physiological, or purpose-specific
Nodding thistle (*Carduus nutans*)	Rangeland	Insect–herbicide	Vertical/physiological
		Insect–plant competition	Vertical/ecological
St. John's wort (*Hypericum perforatum*)	Rangeland	Insect–fire	Vertical/ecological
		Insect–plant competition	Vertical/ecological
Water hyacinth (*Eichhornia crassipes*)	Aquatic	Insect–herbicide	Vertical/physiological,
		Insect–pathogen–herbicide	or purpose-specific
Floating fern (*Salvinia molesta*)	Aquatic	Insect–herbicide	Vertical/purpose-specific, or physiological
		Insect–fertilizer	Vertical/physiological

[a]See text for details.
[b]PSA: partially sequential application.
(From Refs. 6–10.)

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,[20] or with specific formulation and delivery techniques of microbial herbicides.[21] 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.[22] 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.[3,7]

FUTURE DIRECTIONS

When weeds are no longer regarded as a problem to be resolved by curative tactics, then prevention becomes the keyword and integrated cropping management the new concept, of which integrated weed management is an important component. To integrate soil, crop, and weed management effectively, much work remains to be done by scientists spanning a broad range of disciplines.[4] 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.[23] 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 aims at crop production in a weed-free environment, but simply at 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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