The papers in this volume of Topics in Canadian Weed Science were presented at a symposium held during the Canadian Weed Science Society - Société canadienne de malherbologie (CWSS-SCM) meeting held in Halifax, Nova Scotia in December 2003. The topic of weed management in transition was chosen as the symposium theme because weed science has been going through exciting and challenging times across Canada. How we control weeds in crops, the public demand to know how food is produced, the impact of techniques on the environment, and the growing demand for organically produced food are all exerting demands for changes in weed science technologies. These issues and others stimulated research in integrated weed management, in developing alternative control methods, and in determining the environmental impact of herbicides. We now have a continuum of production practices from conventional agriculture relying on herbicides to organic systems where these are not used.

Weed management options now place greater emphasis on the use of different control methods and are now more holistic and integrated, not only in the cropping year but also in the longer term rotation. In this symposium, we asked our speakers to discuss future challenges in weed science. They have presented their viewpoints about the growth and potential of markets for organic products and organic weed management methodologies in crops, examined the state of development of biological control systems and the progress to low risk herbicides and associated technologies for Canadian agriculture, and emphasized the need to have weed science conduct research on basic principles to improve our understanding of mechanisms. The symposium highlights the diversity of research and the transition taking place in weed science and notes that we are at a stage where we need to closely examine the focus of future research and how we can use new technologies to advance a better understanding of weed biology and its interaction with crop production. Weed scientists need to work together and with related plant science disciplines to develop suitable systems for Canadian agriculture and to integrate these into a sustainable, highly productive agriculture that has minimal impact on the environment.

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ISBN 0-9688970-2-9

9 780968 897027

Weed Management in Transition

Topics in Canadian Weed Science Volume 2

Weed Management in Transition

Edited by Jerry A. Ivany

Canadian Weed Science Society
Société canadienne de malherbologie

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Edited by

Jerry A. Ivany

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(ISBN 0-9688970-2-9)
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Citation for Volume:

Ivany, J. A., ed. 2005. Weed Management in Transition. Topics in Canadian Weed Science, Volume 2. Sainte-Anne-de Bellevue, Québec: Canadian Weed Science Society – Société canadienne de malherbologie. 84 pp.

Citation for Chapter:

Author(s). 2005. *Title.* Pages xx-xx *in J. A. Ivany*, ed. Weed Management in Transition. Topics in Canadian Weed Science, Volume 2. Sainte-Anne-de Bellevue, Québec: Canadian Weed Science Society – Société canadienne de malherbologie.

Foreword

The discipline of weed science in Canada has come a long way since the first formal Canadian weed committee, the Associate Committee on Weed Control, held its inaugural meeting in Edmonton, Alberta in 1929. Eighteen committee members discussed the ever increasing problem of weeds on Canadian farms. Since then, similar committees including the Canada Weed Committee, the National Weed Committee and the Expert Committee on Weeds, have met regularly to address the challenges associated with weed management in Canada. Weed science as a scientific discipline blossomed after the introduction of 2, 4-D in the 1940s. The numerous synthetic herbicides that followed 2, 4-D heralded a new and exciting era for weed control, and herbicides became the dominant control strategy for the next forty years. In the 1980s, however, it became apparent that more integrated approaches to weed management were required. The prolonged use of some herbicide classes resulted in the selection of resistant weed populations while other herbicides had a propensity to persist in soil and groundwater for long periods resulting in both production and environmental problems. These issues and others stimulated a renewed interest in topics such as integrated weed management, weed biology and ecology, biological weed control, application technology, and the environmental impact of herbicides. In response to these challenges, a vibrant, new weed science society emerged in Canada in 2002.

Today, the Canadian Weed Science Society - Société Canadienne de Malherbologie, includes a rich mixture of members involving federal, provincial and municipal government employees, multinational herbicide industry researchers and managers, university professors and graduate students, contract researchers, and consultants and industry agronomists. Our goals are (1) to establish and maintain a process for sharing and disseminating weed science knowledge in Canada; (2) to provide a forum for discussion of weed management issues in Canada; and (3) to take a proactive stand on behalf of all stakeholders on issues related to weed management at provincial and federal levels.

I am pleased to introduce the second volume in the series - "Topics in Canadian Weed Science". It is our intention to utilize this publication format to more consistently publish and distribute the relevant proceedings of our annual workshops and symposia. I encourage you to visit our website for further information regarding our society (www.cwss-scm.ca).

Neil Harker
President, 2002-2003
CWSS-SCM

Preface

Welcome to the second volume of *Topics in Canadian Weed Science,* which is published periodically by the Canadian Weed Science Society – Société canadienne de malherbologie (CWSS-SCM). The series provides current information, reviews, research results and viewpoints on weed-related topics and issues. It is intended to advance the knowledge of weed science and increase awareness of the consequences of weeds in agroecosystems, forestry, and natural habitats. The topics addressed are diverse and exemplify the challenges facing the various stakeholder groups that make up CWSS-SCM.

This volume is a compilation of peer-reviewed papers based on oral presentations made at the plenary session of the 2003 CWSS-SCM annual meeting held in Halifax, Nova Scotia. "Weed Management in Transition" was the theme with a diverse group of speakers discussing future challenges in weed science.

The CWSS-SCM Board of Directors expresses their gratitude to Glen Sampson and the Halifax Local Arrangements Committee, the contributing authors, reviewers, and the editors who have made this publication possible. We also ask the readers of this volume to publicize this series to a more global audience. Other volumes include *Field Boundary Habitats: Implications for Weed, Insect, and Disease Management* and *Soil Residual Herbicides: Science and Management.*

Eric Johnson
Publications Director
CWSS-SCM

Acknowledgements

Cover

Top photograph: Photograph of a Lely flex-tine harrow cultivating a cereal field in Prince Edward Island. This image provided by Jerry A. Ivany, Agriculture and Agri-Food Canada, Crops and Livestock Research Centre, Charlottetown, Prince Edward Island, Canada.

Bottom photograph: Photograph of an organic onion field in south-western Quebec. This image provided by Daniel C. Cloutier, AgroByte, 102 Brentwood Rd., Beaconsfield, Quebec, Canada.

Cover Design for the Series: Ralph Underwood, Agriculture and Agri-Food Canada, Saskatoon Research Centre, Saskatoon, SK.

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The Editor would like to thank the following people for their assistance in reviewing the papers contained in this volume. Their comments, constructive criticisms, and suggestions have been greatly appreciated by the authors.

Barbara Booth	Eric Johnson	Rene Van Acker
Allan Hamill	John O'Donovan	Alan Watson
Donald Hare	Glen Sampson	
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Weed management in transition

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Introduction

Weed science has made a major contribution to crop production over the years through early research on weed biology and development of physical weed control techniques and cultural practices in cropping systems. Weed control advanced to levels where weed competition could be nearly eliminated from crop production when selective herbicides were discovered. The period after discovery of 2,4-D was one of rapid advances in new herbicide development as more and more families of herbicides with differing selectivity were discovered.

We have noted that the introduction of new herbicides has been decreasing, rates of application have gone from kg / ha to g / ha, and low risk products are now the standard for any new products introduced into the market,. The new herbicides are more specific in their actions against weed families and species, are targeted to biological systems, and modes of action. The cost of introducing new herbicides is reaching such a high level that many crops once considered major have been relegated to minor crop status. Due to the high financial risk for companies, many crops presently are not considered candidates where returns on investment for new herbicide development can be recouped and no, or few, new herbicides are being introduced to the market. The problem is being compounded as well, as older herbicides are re-examined and do not meet today's more stringent health and environmental safety requirements resulting in removal from the market. Added to these problems is the development of weed resistance to herbicides that can occur very rapidly in some herbicide classes.

In recent years, our science has been going through exciting and challenging times with many changes happening to how we control weeds in crops and how herbicides are viewed by the general public. The public is questioning more and wants to know how food was produced and the impact that food production has on the environment. Although organically produced food is not a large segment of the market at present, its demand increases very rapidly every year. Systems that minimize the use of pesticides have been developed so that we now have a continuum from conventional agriculture to organic systems.

Proponents of each system have valid reasons for their system of production. It is important that weed scientists work together as a group to develop systems that are suitable for Canadian agriculture and to integrate these systems so that the best are adopted.

Weed management options now place greater emphasis on the integrated use of different control methods. We now realize that the whole system must be taken into account and crop and weed biology as well as crop management factors are being researched more and more to elucidate the important aspects that can be harnessed to achieve weed control. All of this must be done to maximize yield but at the same time provide the most economical cost to the producer and without damage to the environment. Methods are now more holistic and integrated, not only in the cropping year but also in longer term rotation.

We have a good understanding of the competitive effects of weeds on crops, when competition takes place, and perhaps what it takes to remove weeds that are present in many large acreage field crops using cultural, physical and chemical methods. In this symposium our speakers have given an excellent overview of weed control using organic methodologies (Frick), biological control systems (Boyetchko); and how the chemical industry looks at the various aspects of risk in the provision of herbicides for Canadian agriculture (Macleod et al). The growth and potential of the developing market for products produced using organic methods is also presented (Morton).

All production systems use techniques and technologies that have been available and refined for several years but have not seen major changes during the past several years. Changes have been gradual and successful, but we are now at a time in weed science where we need to evaluate and determine the best path to follow to develop successful weed management technologies that have minimal effects on the flora and fauna of the soil, air, and aquatic environments. Weed science is in transition and we are at a stage in the development of our science, as is so aptly presented in the paper by Morrison, where we need to closely examine what will be the focus for future weed science research and how we can collaborate and integrate with basic science disciplines that will allow us to have a sustainable, highly productive agriculture in Canada.

Weed control in organic systems

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Historically, we have taken an adversarial approach to weeds. In this paper, I suggest that we consider weeds as bio-indicators of ecosystem processes. The goal of weed management in organic systems is not to eradicate weeds, but to favour the crop and learn environmental lessons from the weeds, taking a long-term perspective. Organic weed management depends on the foundation of good solid agronomy: preventing potential problems, diversifying the cropping system and dealing directly with outbreak situations. Most weed species that are abundant in organic fields are common in conventional fields, though organic producers consider genetically engineered plants to be especially problematic weeds. Many potential weed problems can be averted through management activities and agronomic practices that diversify the cropping system and the weed environment. Common practices include rotation of crops; use of green manure and cover crops, forages, mulches, intercropping; use of highly competitive crops and crop cultivars; use of allelopathic crops; and matching crops to fertility. Management practices that favour crop competitiveness include: increased seeding rate, varied seeding dates, and practices that encourage beneficial organisms such as mycorrhizae and insects. Livestock operations offer producers flexibility in managing weeds. Although there is a move towards reduced tillage, tillage remains a useful tool, both in and out of crop. Alternatives include mowing, over-cutting and thermal control. Organic herbicides offer some potential. The weed management challenges in organic systems are in understanding the ecological relationships between weeds, crops and other aspects of the cropping system; in varying practices to avoid a build up of weeds suited to a single practice; and in integrating weed management with other farm goals.

Introduction

Historically, we have taken an adversarial approach to weeds. Weed Science has been primarily the science of weed control, with eradication seen as the ideal and weed biology merely as a way to “know thine enemy”. This approach has not been successful. Despite 50 years of chemical use, weed problems have not been eliminated from conventional fields. Instead, there is growing concern over “collateral damage” from inappropriate and excessive herbicide use.

Recently, and especially in response to herbicide resistant weeds, weed scientists have moved toward a more integrative approach. This approach, characterized as “many little hammers” (Liebman and Gallandt 1997) depends less on a single highly effective chemical and more on the additive effects of many chemical and non-chemical weed control strategies.

In organic agriculture, there are fewer quick fixes, and weed management is necessarily more focused on causality than reaction, on ecology than chemistry, on management of the cropping system than on weed control. Thus, organic weed management is integrated weed management and weed scientists and organic farmers have much to learn from each other.

In this paper, I suggest that we may be ready to take the next step in our relationship with weeds. We may be ready to focus on biological processes that work with nature, using a collaborative rather than adversarial model. If, as suggested in this session title, weed science is in transition, perhaps the transition may be to a paradigm where weeds are bio-indicators of ecosystem processes rather than simply being annoyances that thwart our ambitions of control.

Weeds in organic farming systems

Principles of organic farming

The International Federation of Organic Agriculture Movements (IFOAM 2002) lists 15 principles of organic agriculture. Included in these is the production of “sufficient quantities of high quality food, fibre and other products” in a manner compatible with “natural cycles and living systems”, using “cultural, biological and mechanical methods as opposed to reliance on inputs”. Organic agriculture is a relational, systems approach to agriculture and is not simply farming without some technologies.

A certified organic operation is scrutinized annually by trained inspectors to ensure compliance with certification standards that are accredited by national or international bodies. Certified organic products are verified to be compliant with one or more of the organic standards, including Canada’s (Canadian General Standards Board 2004), the American National Organic Program, IFOAM, or others.

Prevalence of weeds in organic and other systems

Weeds are usually defined as “plants growing where they are not wanted”. Plants identified as weeds are typically viewed as undesirable because they reduce yields, increase dockage, host crop diseases or pests, complicate grain storage, make crops more difficult to harvest, taint crop flavours or appearance and/or are poisonous. In some situations, plants that are usually considered to be weeds can be beneficial by capturing nutrients and making them more available to subsequent crops, hosting beneficial insects and microbes, providing ground cover, increasing humidity within the canopy, indicating field conditions, and providing physical support.

Some organic producers have a less adversarial approach to weeds than those who advocate weed eradication. Often organic producers have access to certified organic seed cleaning facilities. This allows volunteer crops to be removed from the main crop and sold for profit. Weed seeds may be "dockage" for conventional farmers, but organically grown weed seeds can be sold into the often lucrative market for organic livestock feed. One organic farmer found that wild oats (*Avena fatua* L.) supported the growth of lentils (*Lens culinaris* L.), keeping the crop from lodging, improving crop aeration, reducing disease problems, and holding the swath in place, making harvest easier. The wild oats were subsequently screened out and used for feed. These changes from weeds as a liability to weeds as an asset reduce a producer's need for aesthetic weed control. Finding a market for weed seeds can encourage producers to set the combine so that fewer weed seeds are returned to the field, reducing future weed populations.

A series of surveys in Saskatchewan indicated that the weed species that occurred in abundance in organic fields are also common in conventional fields. Generally, organic fields had greater numbers of weeds and a greater diversity of weed species (Frick 1993; Leeson et al. 2000; Buhler et al. 2002; Leeson et al. 2003). Wild mustard (*Sinapis arvensis* L.) and lamb's-quarters (*Chenopodium album* L.) and either Canada thistle (*Cirsium arvense* (L) Scop.), bluebur (*Lappula squarrosa* (Retz.) Dumort.) or green foxtail (*Setaria viridis* (L.) P. Beauv.) were especially common in organic systems (Frick 1993; Leeson et al. 2000; Buhler et al. 2002; respectively). In a survey of Manitoba, Saskatchewan and North Dakota organic farms, farmers reported the greatest problems from wild mustard, Canada thistle and redroot pigweed (*Amaranthus retroflexus* L.) (Entz et al. 2001). Leeson et al. (2003) reported green foxtail and lamb's-quarters as characterizing organic plots in a long term rotations study in Saskatchewan. Interestingly, wild mustard and Canada thistle were also identified as problematic weeds in organic farming in the United Kingdom (Beveridge and Naylor 1999).

Weed numbers are frequently, but not always higher under organic management. Hulting et al. (2003) found that wild oat densities actually decreased during the transition to organic in tests in Montana. Crop diversity was effective at keeping weed levels down during the transition. Ullrich et al. (2003) reported that there was no long-term increase in the weed seed bank during the first six years of organic management. The weed seed bank was influenced by weather, by crop and by the success of weed management in previous years. Weed seed mortality was high, especially in longer rotations.

In Saskatchewan, differences between organic and "conventional" systems were not the major determinants of the weed flora. Differences between years were more important (Frick 1993), as were differences between rotations that included perennials and those that were strictly annual (Leeson et al. 2000).

Organic producers are particularly vulnerable to contamination from genetically engineered (GE) crops. Organic standards disallow GE plants (Canadian General Standards Board 2004; Agricultural Marketing Service n.d.) and thus GE plants can affect organic certification status, whether intentionally seeded or not. Organic producers are compelled to be vigilant to prevent the introduction of GE plants to their fields, and to rogue plants that find their way into organic fields. In Saskatchewan this has virtually eliminated canola (*Brassica napus* L.) from organic producers' cropping options. The Danish Parliament is the first to enact coexistence legislation that specifies the relationship between GE and organic crops and specifies the payment of damages to organic farmers resulting from GE contamination (Boel 2004). The National Organic Program of the United States Department of Agriculture states "A variety of methods used to genetically modify organisms … are not considered compatible with organic production."

Organic weed management options

Weed management in organic systems is accomplished by managing farm inputs and activities. Emphasis is on healthy soils, crops and livestock. The goal is not to eliminate all weeds, but to favour the crop and use the weeds as indicators of soil and other environmental conditions. Using diverse rotations and varying practices prevents many weed outbreaks. Organic weed management depends on the foundation of good agronomy: preventing new problems, diversifying the cropping system and dealing directly with outbreak situations.

Weed management techniques available to organic farmers often may not give the level of control that is expected of herbicides. Often organic weed management requires a cumulative effort and a long-term perspective that integrates a multitude of practices. Weeds are less likely to adapt to a diversified management system (Harker and Clayton 2003).

Prevention of new weed problems

Introduction of new weeds is largely prevented by following standard agronomic practice: use of clean seed, isolation of field margins, cleaning of equipment between fields. Organic standards provide a number of guidelines to reduce weed introductions (Canadian General Standards Board 2004). For instance, seed must be free of GE organisms. In crops that may be contaminated, seed intended for sowing must be analyzed and verified free of GE seed. This stringent requirement for seed purity reduces GE weeds.

Machinery used in conventional fields must be thoroughly cleaned before moving to organic fields. As well as preventing chemical contamination, this practice limits the movement of weed seeds and vegetative propagules.

Buffer strips are required between organic and conventional production. These areas are maintained and harvested separately from the organic crop. Buffers are intended to detect and limit chemical drift, but separate handling probably reduces the movement of weeds between conventional and organic crops.

Organic regulations are beginning to require that seed used for organic production be grown organically. Organically grown seed may have a greater potential for weed seed contamination than conventionally grown seed (Bond and Lennartsson 1999). This may be problematic, unless seed cleaning is particularly effective.

Immigration of weeds into fields can be slowed, but not halted, by vigilance. Some seed movement is inevitable, due to birds, mammals, movement from wind, etc. Manual roguing is recommended for plants that may potentially be GE, or those that are pollen receptors for GE plants. Other new and invasive species may also be rogued.

Reducing the spread of weeds within the field is also important. Chaff collection can remove seed spread by combining. Managing patches within the field can reduce the spread of localized populations.

An important aspect of reducing weed problems is in recognizing when the presence of weeds is not a problem. If weeds are not causing additional yield loss, and seed set from those weeds is considered within the overall management of those fields, the current weed situation may not be problematic. O'Donovan and Sharma (1983) clearly showed that the later weeds emerge, the less crop loss they cause. Late emerging weeds in competitive crops may be suppressed. Small stature crops such as lentil or flax (*Linum usitatissimum* L.) may not be able to suppress late emerging weeds, but these crops may retain yield in the presence of late emerging weeds. Recent studies have indicated that late emerging weeds may not have a significant effect on the seed bank (Chandler et al. 2001, Swanton et al. 1999).

Alternately, if a field has a serious outbreak of weeds, such that crop loss would be severe and inputs into the seed bank excessive, an organic producer may terminate a crop in order to prevent future problems.

Many potential weed problems can be averted through agronomic practice. A number of techniques are summarized in the next section.

Diversify the cropping system

Weeds grow within an environment that is strongly influenced by the interaction of general climate, soil characteristics, specific weather, and agricultural practice. In the long term, a producer can improve soils by incorporating soil building crops and by reducing tillage. Wind and moisture patterns can be subtly changed by planting shelterbelts or grassing waterways. But the main impact a producer has on weed growth in the short term is through crop management. Each crop management activity affects the environment for weed emergence and growth. Varying crops and management activities prevents weeds from gaining a consistent advantage. Severe weed outbreaks indicate cropping decisions that were not effectively matched to the weed environment (or the weather).

Rotation of crops, growing competitive crops and including green manure crops were the top three ranked weed management practices for organic producers in Saskatchewan (Knight and Shirtliffe 2003). Various tillage practices (both in and out of crop), along with using higher seeding rates were also ranked relatively high. In all, producers ranked 19 different practices among their top 3 rankings.

Rotations: Crop rotation is central to organic farming. Crop rotations minimize problems such as weed, insect or disease outbreaks; improve soil structure and fertility; and increase crop yields (Young 1808; Liebman 1988; Reganold et al. 1990; Jordan 1992; Bullock 1992; Liebman and Dyck 1993).

Cover crops, forage crops, green manures, mulches and intercrops: Adding crops that increase plant cover and fill in gaps in the canopy reduces the weed niche. Management practices such as mowing, incorporation or mulching are detrimental to weeds in the crop.

Cover crops and green manures can have weed suppressing qualities. Liebman and Dyck (1993) reviewed over 50 studies on cover crops and reported that weed biomass was reduced in almost all of them. Cover crops may shade the ground, reducing temperature fluctuation and the weed seed germination that depends on it (Ghersa et al. 1994). They reduce available resources for weeds and change the environment for weed germination (Liebman and Davis 2000). Cover crops can increase both the abundance and diversity of soil microorganisms. This may increase the potential for soil borne organisms detrimental to weeds, and for the successful colonization of biocontrol agents (Boyetchko 1996). Carabid beetles (this family includes many weed seed predators) can be more abundant and active under cover crops than in soils free from residues (Hartwig and Ammon 2002). Under favourable conditions, fall seeded crops such as fall rye (*Secale cereale* L.) and winter wheat (*Triticum aestivum* L.), seeded after harvest and killed in the spring, reduced weed populations (Moyer et al. 2000).

Inclusion of perennial forage legumes in rotations has distinct benefits, reducing annual weeds by providing early and season long competition, and the opportunity to mow before annual weeds set seed (Ominski et al. 1999; Leeson et al. 2000; Clapperton et al. 2003).

Legumes are commonly grown as a green manure in organic agriculture, because of their ability to supply nitrogen. Legumes can also provide significant weed control (Caamal-Maldonado et al. 2001).

Winter-killed cover crops form a layer of mulch in the spring that further suppresses weed establishment and growth (Swanton and Weise 1991). Wiens (2004) reported good weed suppression with alfalfa mulch spread over wheat either before emergence or at the 4-leaf stage. A mulch layer may reduce weed seed germination, possibly due to reduced moisture, oxygen, or light; unfavourable temperatures or carbon dioxide concentrations, or the build up of phytotoxic substances. A mulch layer may need to be 10 to 15 cm deep to effectively discourage weed growth (Ozores-Hampton 1998), or only 3-cm (Ligneau and Watt 1995) depending on the material used.

The presence of winter annual or living mulches will help control weeds and may prevent or slow down the invasion of new weeds that might otherwise become a problem. The idea of using a living mulch as a ‘‘designated weed’’ and learning to live with it is very appealing (Hartwig and Ammon 2002).

Intercropping and undersowing offer scope for weed suppression in a rotation (Baumann et al. 2000). Probably the most common intercrop in Saskatchewan is a cereal underseeded to a legume (Smith 1995). This combines both fertility and weed management. Underseeding clover in cereals suppressed weeds (Dyke and Barnard 1976; Hartl 1989).

Intercrops may be used for green manure, forage, or as seed crops, and the decision between these options may be made depending on the amount and stage of weed growth in the field. Intercrops tend to be more weed suppressive than many, but not all monoculture crops (Mohler and Liebman 1987; Lanini et al. 1999; Szumigalski et al. 2002).

Competitive crops and cultivars: According to Harker and Clayton (2003), “a healthy competitive crop is the key to weed management in any cropping system.” The competitive ability of a crop can be viewed in two different ways: ability to maintain yield in the presence of weeds and ability to suppress weeds. Traits leading to these two might be different, but some studies indicate that tolerance and suppression may be correlated (Lemerle et al. 1996; Watson et al. 2002). Traits associated with competitive ability include rapid germination, early emergence, seedling vigour, rapid leaf expansion, large leaf area, large stomate number, rapid canopy development, high tiller number, retention of tillers, increased plant height, early root growth, allelopathic ability, extensive leaf display and extensive roots (Pavlychenko and Harrington 1934; Swanton and Wiese 1991; Wyse 1994; Lemerle et al. 1996; Spears and Wright 1999; Mason et al. 2004).

Allelopathy: Allelopathy generally refers to an inhibition of growth due to secondary metabolites produced by a plant, or from a decomposing plant. Allelopathic crops such as barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), wheat, rye, canola, black mustard (*Brassica nigra* (L.) WJD. Koch), other mustard spp., buckwheat (*Fagopyrum esculentum* Moench.), red or white clover (Trifolium pratense L.), sweet-clover *(Melilotus officinalis* (L.) Lam.), hairy vetch (*Vicia villosa* Roth.), creeping red fescue (*Festuca rubra* L.), tall fescue (*Festuca arundinacea* Schreb.), and perennial ryegrass (*Lolium perenne* L.) used in rotation, may help suppress weeds in subsequent crops (Liebman 1988; Teasdale et al. 1991; Boydston and Hang 1995; Weston 1996). Allelochemicals may be more effective at suppressing small seeded weeds than larger seeded crops, because of the shallower depth of the smaller seeded plants, and because of the weeds’ greater root surface area which may give them greater contact with the chemicals in the soil (Liebman and Davis 2000). Batish et al. (2001) provides an extensive summary of allelopathic crop plants. Weston (1996) has reviewed the use of allelopathy in agriculture.

Seeding rate: High seeding rates give the crop an edge in early competition and allow for some damage from post-seeding or pre-emergence tillage. An increase of 25% above normal is often recommended (Canadian Organic Growers 2001). Higher than normal seeding rates reduced weed numbers in peas (*Pisum sativum* L.)(Townley-Smith and Wright 1994) weed biomass in barley (Kirkland 1993) and wheat (Mason et al. 2004; Khan et al. 1996; Wilson et al. 1995) and pea, chickling vetch (*Lathyrus sativus* L.) and lentil used as green manure crops (Lawley and Shirtliffe 2004). The benefits of high seeding rates may be greater under fertile conditions than infertile conditions (Beavers, unpublished data).

Timing: Crops compete more successfully if they emerge before the weeds (O'Donovan and Sharma 1983). This can be accomplished in two basic ways: by seeding the crop before weeds emerge, or seeding late into a depleted weed seedbank.

Early seeding is particularly successful with cereals or pulses like pea and lentil when the weed flora is dominated by C4 weeds such as green foxtail or redroot pigweed. Fall seeded winter annual crops are well advanced by the time annual weeds would normally emerge.

Late seeding is an effective option when the weed flora is dominated by weeds that germinate early, such as wild oats or lamb's-quarters. Weeds are allowed to emerge, sometimes encouraged by a light tillage, and then removed by tillage at seeding, or before crop emergence. This depletes the seedbank in the surface layer of soil and reduces subsequent weed emergence (Bond and Grundy 2001).

Varying seeding times allows strong competition with weeds of different phenology, and prevents a selective advantage to weeds of any particular life history.

Myc*orrhizae*: Arbuscular mycorrhizal fungi (AMF) can benefit plant communities through their effect on soil structure, water relations and nutrient status. They provide an advantage to mycotrophic plants specifically (those that form associations with AMF) by giving them greatly increased access to soil nutrients such as phosphorus, nitrogen, calcium, etc. (Jordan et al. 2000).

Mycorrhizal crops have an advantage in low nutrient fields with non-mycorrhizal weeds (Dalpe and Monreal 2004). Crops such as wheat, barley, corn (*Zea mays* L.), flax, sunflower (*Helianthus annuus* L.), and potato (*Solanum tuberosum* L.) can benefit from AMF. Non-mycorrhizal weeds can be severely reduced in strongly mycorrhizal environments. Families that are predominantly non-mycorrhizal include some problematic weeds: *Amaranthaceae, Brassicaceae, Chenopodaceae, Polygonaceae.* Wild mustard, lamb's-quarters, and wild buckwheat (*Polygonum convolvulus* L.) are non-mycorrhizal (Boyetchko 1996). Families that often are mycotrophic, such as *Poaceae* and *Compositae* include agricultural weeds that are non-mycorrhizal. Thus it is likely that AMF may disadvantage many, even most, weeds (Jordan et al. 2000).

Mycorrhizae and their associated microbes enhance growth and health of mycotrophic plants (Linderman, n.d.) and can alter microbial community dynamics away from dominance by plant pathogens (Hooker and Black 1995). Jordan et al. (2000) hypothesize that AMF may even change the functioning of weed communities so that weeds become more beneficial in the function of agro-ecosystems, by improving soil quality and facilitating the growth of beneficial organisms.

Arbuscular mycorrhizal fungi (AMF) are favoured by many of the common management practices in organic farming, such as elimination of synthetic fertilizers, increased emphasis on legume crops, replacement of black fallow with green manure, and on the Canadian prairies, low incidence of non-mycorrhizal crops of the *Brassicaceae* (Boyetchko 1996). AMF are inhibited, however, by tillage. The use of pesticides and fertilizers reduces the effect of AMF in conventional systems, but they can be relatively important in organic systems. In long-term experimental plots, Mäder et al. (2000) and Entz et al. (2004) found more AMF in organic plots than high input plots.

Soil fertility: Fertility management is an important aspect of weed management in organic systems. Crops and weeds may differ in their resource requirements, and thus weeds may be managed by nutrient adjustments, and weed abundance can indicate soil nutrient status (Tilman and Tilman 1999).

Fertilizer studies often show that weeds benefit more from added fertility than crops do (Alkamper 1976, Carlson and Hill 1985, Jrnsgård et al. 1996). Some weeds may thus be at a disadvantage at low nutrient levels, or where nutrients are released slowly, both of which may be evident in organic systems. Shipley and Keddy (1988) found that plants with the highest maximum growth rates were often those that lost advantage fastest under deficient nutrient conditions. Blackshaw et al. (2003) showed that several weed species increased their growth rate more than crop plants at increased nitrogen rates. Entz (2004) showed that fertilizer application without herbicide increased weed biomass relative to treatments without either fertilizer or herbicide. These studies suggest that at excess levels of fertility, weeds can be more competitive. An effective organic system integrates fertility and weed management.

Dealing directly with outbreak situations

Even with prudent agronomic practice and a thoughtful, tolerant attitude, there are times when preventative techniques are not successful. Direct weed control is sometimes necessary to prevent undesirable levels of crop loss. These techniques can be categorized as physical, chemical or biological.

Physical Weed Control: Tillage is often seen as the organic alternative to chemical weed control. Concerns over the damaging effects of tillage on soil quality, soil organisms, and erosion potential are leading organic producers to seek alternatives that reduce tillage or that that reduce soil disturbance during tillage. Generally this includes lighter tillage implements, shallow tillage, reduced incorporation of green manures, and potentially, the elimination of fall tillage.

Out of crop tillage: When moisture is adequate, and erosion potential is low, tillage can be used for weed control after harvest and/or before seeding (Foster 1996). Fall tillage can be particularly effective at reducing the root reserves of Canada thistle, and thus its potential to cause problems in following crops.

Spring tillage aerates and warms the soil, and encourages the emergence of weeds. An additional tillage operation with, or just prior to seeding can result in a clean seed bed and a head start for the crop.

Black summerfallow is generally discouraged in favour of green manure and cover crops.

In crop tillage: Mechanical weeders include cultivating tools such as hoes, harrows, tines and brush weeders, cutting tools like mowers and over-cutters, and dual-purpose implements like thistle-bars. A review of several implement types is given in Bond and Gundy (2001).

Harrowing (blind harrowing) or rod weeding after seeding but before the crop emerges can be useful if weeds emerge before the crop. Deep and delayed seeding improved the effectiveness of pre-emergence tillage in peas (Johnson 2001).

Tillage with a drag or flex harrow after the crop emerges can also be effective. Crop injury is a concern, but can be minimized by higher seeding rates to compensate for losses and by reducing the aggressiveness, either by adjusting the settings on a tine harrow, or by reducing speed (Johnson 2001).

Selectivity of harrowing seems to result both from differences in seed size and from the different anchorage of crop and weeds. Some plants are killed by covering (Kurstjens and Perdok 2000; Baervaldt and Ascard 1999) while other plants are killed by uprooting (Kurstjens et al. 2000; Kurstjens and Kropff 2001). To be killed by burial, plants need to be buried totally, but plant size, angle and growth habit influence the depth of covering required (Baerveldt and Ascard 1999).

Harrowing is most effective against weeds that emerge before or only slightly after crop emergence. These are the weeds that compete most strongly with the crop and cause the greatest losses. Because timing is important for selectivity, effective harrowing is highly dependent on favourable weather (Hatcher and Melander 2003).

Interrow cultivation: Cultivation can be used for weed control between rows for crops that are widely spaced. Problems arise with interrow cultivation because weeds within the rows are not killed, and can be very competitive (Johnson 2001).

Over-cutting: Clipping weeds above the canopy of short stature crops such as flax and lentil has proven successful for some organic producers. They find greater success in models that cause greater damage to the tops of the weeds such as wild mustard, wild oats and Canada thistle. In preliminary research trials wild mustard, wild oat and lamb's-quarters recruitment was reduced by such weed clipping in the previous year (Johnson and Hultgreen 2001)

Mowing: In perennial forages, mowing can be an effective part of weed management. Forages are often more competitive than weeds after mowing. Many weeds, such as wild oats or Russian thistle, can be used in green feed if cut before seed set. Cutting early, as grazing, silage or hay can reduce annual weeds (Schoofs and Entz 2000; Harker et al. 2003).

Mowing can be an effective alternative to tillage where tillage is undesirable. For the control of perennial weeds, mowing at the onset of flowering is most effective. At this time, food reserves are at a low point. The weed will respond by sending up new stems, further depleting its reserves. Mowing at about three week intervals can severely weaken or even kill perennial weeds such as Canada thistle (Ashford 1978).

Thermal weed control: Flaming, infrared radiation and steam have been used for the control of weeds. Methods involve the use of propane, butane or gas burners to generate a direct flame, or to heat either a ceramic or metal burner. Some thermal methods involve microwaves (Marshall 1992). Grasses have a slightly higher temperature tolerance than broad-leaved weeds, allowing thermal weeding to be somewhat selective (Marshall 1992; Ascard 1995).

The high fuel costs prevent these methods from being practical on a large scale for commodity crops, though small-scale applications are possible for high value crops or specialized use (around granaries, in urban settings). Flaming was an effective method of in-row weed control in potatoes, when repeated, or combined with inter-row tillage (Ivany 2003). Steam was most effective on younger plants (Kohlberg and Wiles 2002).

Chemical Weed Control: The list of chemicals approved for weed control in organic farming is limited. Products must be approved by certification bodies and be non-synthetic. Many organic producers are reluctant to accept this form of input substitution.

Vinegar (acetic acid) showed limited potential as a pre-seed or as a post-emergence herbicide in wheat (Johnson et al. 2003), as did pine oil extract (Johnson pers. comm.) Improvements in application technology may increase the potential of some of these compounds (Wolf, pers. comm.).

Biological Weed Control: A review of inundative biocontrol is provided elsewhere in this monograph. Discussion in this paper will therefore be limited to techniques outside of the usual biocontrol arena.

Livestock: Livestock alter the dynamics of weed management on organic farms, offering greater potential for the inclusion of forages and green feed in rotation, mowing weedy areas of crops, saving chaff and utilizing screenings, and fall or winter grazing.

Livestock can be used to target specific weeds: goats for the control of woody plants and thistles, sheep for leafy spurge and thistles, geese for grasses in broadleaf crops, hogs for perennial weeds between crops (Marshall 1992; Anonymous 1994). Fall grazing in annual crops reduces the advantage that winter annual, biennial and perennial weeds have in annual cropping systems.

Encouraging beneficial biota: Many creatures are considered beneficial in agricultural systems. They can be encouraged by the elimination of biocides and by maintaining a diversity of habitats. This might include reducing tillage to maintain soil habitat, maintaining shelterbelts and wooded refuges, sloughs, or borders, and leaving land in native vegetation. Organic principles include maintaining a diversity of habitats on the landscape (IFOAM 2002). In Saskatchewan, wild birds, especially wetland species, were more common on organic farms than conventional farms (Shutler et al. 2000).

Carabid beetles are often considered indicators of system health. Although the benefits of these insects may have been exaggerated by extrapolation of laboratory studies, carabids have been shown to reduce some crop pest insects, such as aphids, flies and moths. Some carabid seed eaters have potential for biological weed control; some have shown a preference for species of foxtail (Lund and Turpin 1977).

Although carabids are negatively affected by deep tillage, no negative effects have been found for mechanical weed control and flaming. Carabids are enhanced by crop diversification, weediness, intercropping and the presence of field boundaries (Kromp 1999).

Building an agronomic package

Weeds fill gaps that remain when crops don't use all of the available resources (Dekker 1997). Reducing the opportunity for weeds, then, includes all the agronomic techniques that improve crop vigour. Although organic techniques for weed management are improving, it would be unwise to rely on any one technique alone. For each agronomic technique, some weeds survive, and these are the ones that contribute to the seed bank. Evolution of resistance need not be limited to herbicides alone (Bond and Lennartsson 1999). To prevent weeds from reaching outbreak proportions, it is necessary to vary techniques or to maintain "operational diversity" (Harker and Clayton 2003).

Integration of management techniques includes consideration of the possible interactions. As previously mentioned, the addition of fertilizers increases weed growth; fertilizers weaken the plants' ability to take up nutrients through other means such as mycorrhizae; effective herbicides reduce not only weeds, but in turn the weed predators. In natural systems, nothing happens in isolation. Managers of organic systems strive to understand these interrelationships. Understanding the interaction between fertility and weeds alone offers significant potential to reduce early season weed impact on annual crops.

It is also important to consider the impacts that weed management techniques have. Each technique has detriments as well as benefits. This is especially clear for tillage, which may be the most effective control for perennial weeds such as quackgrass. Yet we know there are a number of problems with tillage: increased erosion, decreased mycorrhizae, loss of nutrients. Understanding the interactions is important to reduce damage done through farming technology, and to heal the wounds of management.

Residual weeds are often seen as a failure of weed control in high input management, but some residual weed populations may be advantageous. Many examples can be found. Weeds left in canola fields were found to reduce the success of root maggot reproduction (Dosdall et al. 2003.). Living mulch in wheat fields may reduce the ability of *Fusarium* to reach the wheat heads as it splashes up from the soil (Entz, pers.com.). The presence of weeds may do the same. Barley plants exposed to the allelochemicals produced by quackgrass were less attractive to aphids (Glinwood et al. *20*03).

Organic producers deal with complex, highly interdependent, multifactorial systems. Because of their complexity, organic systems may be more site-specific. Although new techniques can be readily adopted and integrated, prescriptive management is less likely to be effective. Effective management remains a dynamic learning activity.

Conclusion

Producers often cite a fear of losing control of weeds as a major disincentive to going organic. Although weeds may become more abundant and diverse on organic farms, this is not always the case, and it is not always a problem if it occurs. Organic farming involves a different approach to weeds, one that is knowledge and planning intensive, rather than input intensive. A narrow view of organic weed management based on reductionist perspectives and input substitution is likely to underestimate interactions among system components and carryover across seasons (Bàrberi 2001). We have much yet to learn about farming systems. High input systems reduce or mask some of the relationships within agroecosystems. Organic systems offer superior opportunities to better understand the interactions among weeds, crops and environment, and to develop holistic systems that are based on sound agronomic principles.

Acknowledgments

I would like to thank the Saskatchewan Organic Directorate who provided early support for my review of weed literature relevant to organic farming, and who have been consistently generous with their time and enthusiasm. I gratefully acknowledge the many farmers who have shared their ideas with me. I thank Ravinder Grewal who helped with the literature search, and Andy Hammermeister, Eric Johnson, Martin Entz, Debbie Miller Roxanne Beavers, Jennifer Bromm, and two anonymous reviewers for helpful comments that greatly improved this manuscript.

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Growing organic markets

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Introduction

These are exciting and challenging times to be involved in food production. With an estimated 20% growth in the organic food industry, sales in this sector have become a bright light in an industry that has experienced little more than 1- 2% growth in recent years. The majority of organic food (85%-90%) consumed in Canada is imported from other countries. Conversely, 95% of the raw organic food supply produced in Canada (mainly grains and pulse crops) is exported to the USA or Europe. Whether organic growers are small and sell direct to the consumer or are large scale producers focusing on wholesale markets, the organic food chain and marketplace is growing and creating new opportunities for all sectors. As the Canadian organic consumer evolves in their food consumption and purchase habits, so will the opportunities for all organic food growers. Processors and manufacturers will also convert some of their production to organic as the consumer demand increases and supplies of organic food inputs become more available.

USA organic market

The organic food market in the United States (US) has experienced dramatic growth over the past few years with sales reaching $10-11 billion in 2003. Sales are expected to reach $20 billion by 2010.[1] This represents approximately 2% of the total food market in the US. The annual rate of growth in organic food production is expected to continue at 15% to 20% compared to a growth rate of <1% for conventional foods[2]. Sales of some products such as organic milk have increased 50% annually[3]. The market penetration of organic products has also been increasing as more mainstream market opportunities have emerged within the retail sector. The pessimistic forecasts are for a market penetration of 2-3% over the next 10 years while the optimists believe the market could reach 10% of total food

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[1] Organic Food Trends 2002, An Industry Snapshot. Nutrition Business Journal, 2003
[2] Organic Trade Association, 2003
[3] Recent Growth Patterns in the US Organic Food Markets. Dimitri, C. and Greene, C.2002. Economic Research Service USDA.

sales.[4] As more processed goods using organic inputs are developed, production of organic products will continue to grow to meet those demands. The retail sector expects to offer the consumer a full range of organic products comparable to what is available for conventional food. Current organic price premiums may decline in the future as more large and competitive companies enter the marketplace.

Canadian organic market

The organic market in Canada has been estimated at $1Billion (US dollars) for 2002. This represents approximately 1.3% of the entire Canadian food industry ($75 Billion). In Canada there are 3,200 certified producers with a combined certified organic land production base of 430,000 hectares[5]. Canada is considered ideal for organic farming due to the large and diverse land base and cooler climate. Organic grain is the fastest growing market segment, and it is the largest volume organic export commodity. Retail and food service sales of organic processed and non-processed products are expected to reach $2 Billion US by 2005.[6] The majority of organic production is exported to the US. The European Union (EU) and Japan are also important export market opportunities. In 1999, Agriculture and Agri-Food Canada published Canada's National Standard for Organic Agriculture, which is a voluntary standard. With the implementation of the National Organic Products Standards (NOPS) in the US, Canada has been given a one year transition period for organic imports. After the transition period has ended US acceptance of Canadian Standards will be required in order for Canadian organic products to enter the US markets. Canada's organic sector could be severely affected if the US rejects Canada's current voluntary organic standards. Quebec however, has independently implemented a mandatory standard which has already been accepted by the US[7]. This provides an export advantage to organic producers in Quebec. BC is the other province in Canada to have implemented mandatory organic standards.

Competitiveness in the organic industry in Canada is increasing as more and more companies attempt to capitalize on the growth in this sector. Major organic food manufacturers and distribution networks are expanding across Canada. For example, companies like Loblaw's has launched "President's Choice Organics" which has increased the exposure of the organic food market to common consumer. British Columbia, Quebec and Ontario are considered the three primary provinces for the production of organic products in Canada.

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[4] Organic Food Trends 2002, An Industry Snapshot. Nutrition Business Journal, 2003

[5] The World of Organic Agriculture. Statistics and Future Prospects. Yussefi, Minou and Willer, Helga. 2003. International Federation of Organic Agriculture Movements.

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[7] The World of Organic Agriculture. Statistics and Future Prospects. Yussefi, Minou and Willer, Helga. 2003. International Federation of Organic Agriculture Movements.

Atlantic Canada organic market

In 2001, food expenditures in Atlantic Canada totalled $5 Billion (based on weekly expenditures of $108.76 per household and 897,190 households[8]). The annual market for organic foods in Atlantic Canada is estimated to be $65 million based on an average of 1.3%[9] of total food purchases being organic. The top selling organic food products categories are fruits and vegetables. Organic meat sales (traditionally the highest sales value category in conventional food products) are only 0.1% of the total organic food market. In 2001, Statistics Canada reported 75 certified organic producers in the Atlantic Canada region, which represents only 3% of all Canadian organic farmers. The distribution of producers is even across the region with twenty three in Nova Scotia (NS), twenty three in Prince Edward Island (PEI), twenty five in New Brunswick (NB), and three producers certified organic in Newfoundland (NF)[10]. The domestic supply of organic products in Atlantic Canada is currently estimated at $6,500,000 annually. There is significant opportunity for future Atlantic Canada organic production to displace imported organic products. The three main wholesalers, distributors and retailers in the Atlantic Canada region are Atlantic Superstore (Loblaw's), Sobey's and Co-op Atlantic. These three companies comprise approximately 95% of the total retail sector[11]. The domestic share of the organic industry ($6.5 million) in Atlantic Canada can be further analyzed to determine the value based on venue of sales. Given that 6% of the total organic retail value is marketed direct to the consumer (6% of $65 Million), it could be concluded that 100 % of the direct to consumer sales is likely local production ($3,900,000). The balance of the domestic value would be marketed through the mass markets and specialty stores and could be a mix of local and other Canadian product ($2,600,000). Local organic production is therefore marketed mainly using direct to consumer marketing channels (60% of total domestic sales).

The future potential for organic food production in Atlantic Canada is similar to the projected expansion in the rest of Canada. Growth is forecast to be 15-20% for the next 7 to 10 years (see figure 1). Sales as a percentage of the total food market are expected to increase from 1.3% to 3.0% by 2010.[12] Optimists in the food industry feel this trend could continue until organic food products reach 10% of the total food consumed. At the current rate of growth, 10% of total food retails sales could be achieved within 15 years.

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[8] Statistics Canada, Income Statistics Division, 2001.

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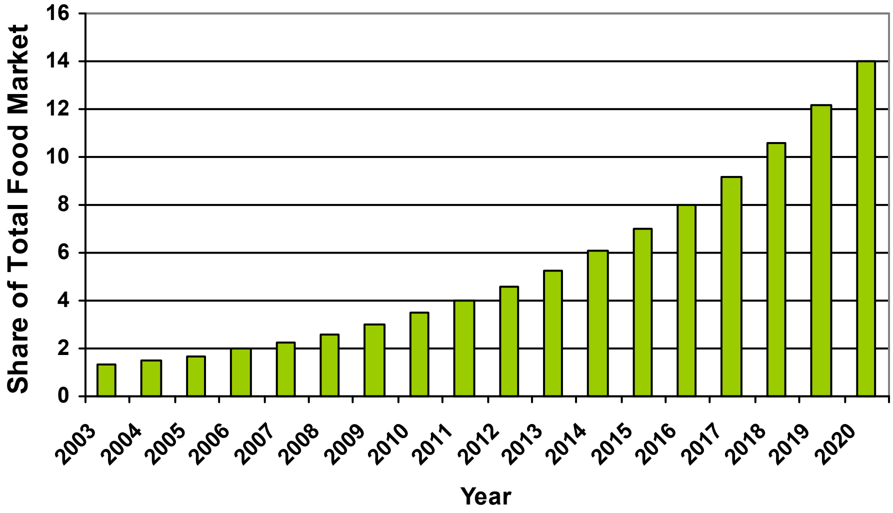

Figure 1. Projected Atlantic Canadian organic market growth at 15% / year. Source: ProAgri Consulting / MHA 2003.

The corresponding retails sales that would be achieved using a 15% growth rate demonstrate the magnitude of the opportunities available to organic food producers. Using a figure of 3% of the total food market as the organic food share, this represents a potential organic industry in Atlantic Canada valued at $150,000,000 (CAN$) by 2010. The challenge for producers will be to take part in the market, not the lack of market opportunity. Turning the market opportunities into sale realities has been and will continue to be the main challenge for organic producers in Canada. Creating success of a market opportunity for any farm business is dependant on the ability of those running the business to achieve these four basic things:

- Creating a product the market wants with the quality and in the quantity it requires.
- Delivering the product to the desired market, when required.
- Producing competitively priced yet profitable products.
- Effective promoting the product to assure future sales and retain or increase consumer demand.

Future trends in organics

The following factors are going to drive the future consumption of and markets for organic food in North America.

- North America's unique baby boom population and the trailing echo generation have the potential to drive organic market growth to levels higher than those experienced by other regions of the world.
- Continuing concerns over food safety in the conventional food supply are causing consumers to look for safer food alternatives.
- The increased concern by common consumers for the health of the environment, where their food comes from and how it is produced will create interest in the organic food production system.
- Better education by the industry and the presentation of more credible scientific research to the public will serve to make the consumer more aware of the benefits of eating organic food and living an organic-based lifestyle.
- The increased demand for processed and value added organic foods will increase, driving the demand for organic inputs for manufacturing.
- As consumers develop more organic-based lifestyles there will be an increase in the use of and demand for organic home and personal care products.
- As larger organic food corporations expand to meet the needs of the chain store markets for more organic food, they will look to research and technology for more efficient organic production systems creating lower organic food costs and prices to the consumer. As the price of organic food moves closer to the price of conventional foods the price deterrent barriers for consumers choosing organic food will fall.

The future growth, success and sustainability of the Atlantic Canada region organic industry will require levels of innovation, collaboration and partnering much different than they have been used to in the past. The key to success in the organic marketplace will be to communicate with current and potential new markets and to build long-term win-win relationships. This will ensure the future of organic food production in Atlantic Canada.

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Biological herbicides in the future

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The early success of biological herbicides such as Collego® and DeVine®, along with a few additional bioherbicide products, created a great deal of interest in their future as a weed management tool. The prototype model for bioherbicides often followed the chemical herbicide industry model, however, their future has come into question because many more potential pathogens have not been commercialized. Critics have pondered whether the prospects for biological herbicides have been exaggerated or whether they can live up to their expectations. A variety of factors that have been attributed to their less than spectacular performance are biological, environmental, technological, and commercial in nature. However, important advances in fermentation and formulation technology and methods for improving efficacy during the past decade have been made. Additional research efforts to understand these factors have provided some answers into addressing how bioherbicides can be used as part of a weed management strategy. Despite the resources that have been dedicated to traditional weed control, particularly chemical herbicides, weeds continue to thrive and adapt in modern agriculture. If we are to build the next generation of biological herbicides, a shift in philosophy of weed management and the role of bioherbicides as part of an Integrated Weed Management (IWM) package is required. Less focus should be on development of stand-alone products but there is a need to focus on weed population management and bring together research teams with diverse expertise that lead to successful integration of biological herbicides as a component of IWM.

Introduction

Since the first introduction of two registered bioherbicides in the U.S. in the early 1980's, there has been a considerable increase in research activities towards the development of plant pathogens to control several important weed species. However, one continues to wonder what the future of biological herbicides will be. The concerted efforts of researchers during the last three decades has resulted in the evaluation of approximately 300 microorganisms (fungal and bacterial agents) and the claims of "potential" for biological weed control (Boyetchko et al. 2002; Charudattan 2000, 2001; Rosskopf et al. 1999). These discoveries have resulted in nine microbial agents that are either registered or have been granted permission for use in five countries and at least two agents that are in the process of registration approval. There appears to be no shortage of microorganisms capable of controlling weeds to be discovered, but the development of these promising agents into viable commercial bioherbicide products is complex, involving a variety of bioprocesses, such as fermentation and formulation that often proved to be major bottlenecks.

A success ratio of developing these organisms into bioherbicides has been conservatively estimated at 20:1, compared to less than 1%, or 1 in 20,000 compounds, that are screened by the chemical pesticide industry (Charudattan 2001). In addition, costs for developing and registering bioherbicides are estimated at US$2 million, compared to US$50 million for chemicals. Despite these disparate comparisons, the question remains why biological herbicides are suffering from limited success and where is the next generation of bioherbicides?

It has been pointed out that scientific efforts in biological weed control have not contributed to the lack of commercial success of biological herbicides, but that researchers have failed to focus on resolving critical technical elements such as formulation and methods for stabilization of living organisms (Zorner et al. 1993). It is true that a great deal of research effort has focused on the search for microbial agents with weed control potential, but technological challenges that include economical methods for mass production and scale-up, viable formulation and application strategies, and shelf life have been encountered and have contributed to the lack of commercial success (Auld and Morin 1995; Boyetchko and Peng 2004; Mortensen 1998). However, the long-term commitment towards biological control has been predominantly supported by public research institutions such as Agriculture and Agri-Food Canada, USDA-ARS, Forestry Canada, and universities (Charudattan 2000), while investment by industry to commercialize this technology has been sorely lacking. In addition, the teams of researchers dedicated to understanding the fundamentals of weed biology and ecology and the agronomists necessary to implement weed management practices, have not been active participants in the application and implementation of biological herbicide technology.

Although chemical herbicides constitute an important and viable weed management tool, weeds continue to thrive and their management depends on the integration of all weed management tools, including chemical herbicides and alternative technologies (Wyse 1992). Moreover, the dominance of the chemical herbicide industry to develop chemical herbicides over the last several decades, with weed eradication being the ultimate goal, has not led to the destruction of various target weeds, including such ubiquitous weeds as wild oat (Harker and Clayton 2004). This review will explore the potential of biological herbicides and attempt to address the needs for future success that will lead to their implementation and practice as an additional weed control tool for integrated weed management (IWM).

Status of biological herbicides

By definition, biological control is the deliberate use of living organisms to control pest populations (Charudattan 1991). The term bioherbicide has often been misused and has led to the general assumption that all microbial weed control agents are weed killers (Crump et al. 1999). Therefore, for the purpose of this review, the definition of biological herbicide (or bioherbicide) will be "the deliberate use of living organisms to directly or indirectly reduce the vigour, reproductive capacity, or effect of weed populations". Microbially-derived chemicals that are chemically synthesized and applied in pure form, in the absence of the living organism, will be considered to belong to chemical pesticide technology (Charudattan 1991).

The commercialization of the first two bioherbicides in the U.S. led to tremendous interest in this concept of weed management. A collaboration between the University of Arkansas, the U.S. Department of Agriculture, and the Upjohn Company resulted in the registration of *Colletotrichum gloeosporioides* f.sp. *aeschynomene* in 1981 as a post-emergent biological herbicide (Collego®) for control of northern jointvetch (*Aeschynomene virginica*) in rice and soybean (Charudattan 1991; Kenney 1986; TeBeest and Templeton 1985). In addition, DeVine® was developed by Abbott Laboratories, in collaboration with the Department of Plant Industries, Florida Department of Agriculture, as a liquid formulation of the soilborne pathogen *Phytophthora palmivora* for control of stranglervine (*Morrenia odorata*) (Burnett et al. 1974; Charudattan 1991; TeBeest 1996; TeBeest and Templeton 1985). Collego® and DeVine® have been commercially available through Encore Technologies (Minnetonka, Minnesota); however, the second registration of Collego® was terminated in the fall of 2003 by the company and its future status as a product is currently unknown (D.O. TeBeest, University of Arkansas, personal communication). The initial success of the first two U.S. registered bioherbicides was followed by the registration of several other bioherbicide products, including BioMal®, the first registered bioherbicide in Canada that was licensed from Agriculture and Agri-Food Canada to industry (Mortensen 1988; Mortensen and Makowski 1989). Although originally developed for commercial use by Philom Bios (Saskatoon, SK), BioMal® was subsequently licensed to Encore Technologies. However, in 2002, further commercial development was terminated. Another bioherbicide, Dr. BioSedge®, is an endemic rust (*Puccinia canaliculata*) registered for control of yellow nutsedge (*Cyperus esculentus*) by Tifton Innovation Corporation (Tifton, GA) but it also is not commercially available (Boyetchko et al. 2002; Charudattan 1991; Rosskopf et al. 1999).

Other bioherbicides have since been developed and commercialized. The foliar-applied bacterial agent, *Xanthomonas campestris* pv. *poae*, is registered for commercial use as Camperico®, in golf courses to control annual bluegrass (*Poa annua*) (Boyetchko et al. 2002; Charudattan 2000; Rosskopf et al. 1999). Stumpout® is an oil-based paste formulation of the wood-decaying fungus, *Cylindrobasidium laeve*, for biological control of wattle (*Acacia mearnssi* and *A. pycnantha*) in South Africa. *Alternaria destruens* is currently undergoing pre-commercial development and U.S. EPA registration review for control of dodder

(*Cuscuta* spp.) in various agricultural crops such as cranberries (Rosskopf et al. 1999). An isolate of *Sclerotinia minor* has demonstrated excellent potential for the broad-spectrum control of dandelion and other broadleaved weeds in turfgrass (Watson and Ahn 2001). Although it has an extremely wide host range, it has been found not to be pathogenic on members of the Poaceae and its host specificity is similar to that of the chemical herbicide 2,4-D. Since this pathogen is considered to have similar or superior efficacy to the industry standard, it is being developed as a bioherbicide (A.K. Watson, McGill University, personal communication).

The broad-spectrum wound pathogen, *Chondrostereum purpureum*, is commercially available through Koppert Biological Systems under the name BioChon™ in the Netherlands for control of a variety of hardwood tree species in plantations (DeJong et al. 1990; Dumas et al. 1997). In Canada, another isolate of the same pathogen is undergoing joint registration in Canada and the U.S. under the name Chontrol™, for suppression of forest weeds in utility rights-of-way, railways, ski resorts, nurseries, and tree farms by MycoLogic, Inc. A temporary registration of Chontrol Paste EP was recently received for Canada and the U.S. and will be converted to a full product registration pending the results of additional toxicology tests (W.E. Hintz and P. de la Bastide, MycoLogic, Victoria, B.C., personal communication). In 2002, a different strain of *C. purpureum* was granted registration in Canada as MycoTech® Paste for deciduous tree control in utility rights-of-way and in conifer release programs (www.hc-sc.gc.ca/pmra-arla/).

Bioherbicide prototype models and expectations

Although researchers have reported numerous successful microbial agents with bioherbicidal potential, this has created the optimistic impression that additional bioherbicides are close to becoming commercially available. Also, the expectation of weed mortality using terminology such as bioherbi-“cides” has generated the illusion that these organisms have or must possess identical features to chemical herbicides and will lead to the eradication or near-kill of weed populations (Auld & Morin 1995; Crump et al. 1999). The fact that biological herbicides are not analogues to chemicals, lacking in some of the features of chemicals, has perhaps led to the opinion by some critics that this technology has failed to deliver the goods. But is this truly the case when in fact we are comparing the traits and benefits of biologically-based technology using the paradigm of chemically-based technology?

The first generation of bioherbicides had a variety of characteristics that were comparable to those of chemical herbicides and deemed to be desirable for their commercial success (Boyetchko & Peng 2004; Charudattan 1991; Mortensen 1998). Successful bioherbicides were expected to provide high efficacy, often resulting in high weed mortality. Other traits considered in early bioherbicide development were host-specificity (i.e. preference for narrow host-range), ease of use, genetic stability, cost-effective mass production, and ability to provide rapid weed control with predictable field performance. While these characteristics are attractive, many biological herbicide candidates have fallen short of meeting these requirements.

Both Collego® and DeVine® were considered great achievements because they provided at least 90% weed control that was effective and consistent (Charudattan 2001). However, their efficacy on single weed species has limited their commercial success, particularly when one considers that most agroecosystems are comprised of multi-species weed communities. It may be difficult to justify for many farmers to use or for industry to market a single product to control a single target weed. In addition, these two products have targeted weeds with specialized markets and limited profit margins (Evans et al. 2001). On the other hand, a product such as Camperico®, with a single economic target, has a high value market in the golf course industry (Charudattan 2001).

The development of *Chondrostereum purpureum* as a mycoherbicide has expanded its utility because of its broad-spectrum activity on a variety of woody tree species such as red alder (*Alnus rubra*), black cherry (*Prunus serotina*), white birch (*Betula papyrifera*), and aspen (*Populus* spp.) (DeJong et al. 1990; Dumas et al. 1997; Shamoun et al. 1996; Wall 1994). Other examples of bioherbicide candidates exhibiting a broad host-range include *S. minor* for dandelion and other broadleaved weed control in turf, *Pseudomonas syringae* pv. *tagetis* on Canada thistle and other Asteraceae weeds and *Sclerotinia sclerotiorum* for control of Canada thistle, dandelion, and diffuse and spotted knapweeds (Brosten & Sands 1986; Mortensen 1998; Riddle et al. 1991; Watson & Ahn 2001).

While broad-spectrum activity is viewed as an advantage for a commercial product, whether it is biologically or chemically based, many chemical herbicides exhibiting this feature may be restricted as to application at particular growth stages of the crop without causing a certain level of crop injury (Heiny & Templeton 1993). Some of the host specificity traits of many biological herbicides may be advantageous since there is a greater assurance that nontarget and beneficial plant species will not be damaged and the bioherbicide can be applied at any growth stage of the crop without injury (Boyetchko & Peng 2004; Heiny & Templeton 1993).

One of the benefits of DeVine® was that it persisted in the soil to provide long-term and residual activity; however, this same trait could also be considered a disadvantage if it creates problems for crop rotations where the crop may be a susceptible target to the bioherbicide pathogen. In addition, from an industry perspective, long-term residual effects can lead to reduced demand for repeat product sales, which can be exacerbated by the fact that the product has a small market potential in the first place (Heiny & Templeton 1993). These issues also hold true for chemical pesticides. In addition, DeVine® must be refrigerated and the product must be made-to-order 30 to 60 days prior to its intended use due to its low stability and thus has limited shelf life (Heiny & Templeton 1993; Rosskopf et al. 1999).

From a technological perspective, Collego® is capable of being economically mass produced in liquid culture fermentation at a commercial scale, but other fungal bioherbicides have not seen this same achievement since many of the prospective fungi cannot readily produce spores in liquid, but sporulate more readily in solid-substrate fermentation (Evans et al. 2001). Unfortunately, high labour costs, inability to control cultural conditions and maintain sterile conditions have been associated with solid-state fermentation (Churchill 1982). BioMal® was not commercialized in Canada due to technical difficulties to mass produce it cost-effectively (Boyetchko et al. 2002).

Unreliable field performance, a reason for the lack of success of many post-emergent bioherbicides, has often been the result of the requirement for long periods of dew or leaf wetness by the microbial pathogen (Auld & Morin 1995; Boyetchko & Peng 2004). Although Collego® and DeVine® perform consistently and with high efficacy in the field, these early prototype models were used under relatively conducive conditions and thus required very simple formulations. Collego® was effective because the target weed inhabits rice paddies where high humidity is normally present (Gressel 2003). In the case of DeVine®, it is a soilborne pathogen and subjected to less fluctuating temperature and humidity.

Challenges

Despite the early success of Collego® and DeVine®, there have been a variety of constraints that have contributed to the failure to commercially develop several subsequent bioherbicide projects (Auld & Morin 1995; Boyetchko & Peng 2004; Boyetchko et al. 2002; Charudattan 1991). These have been categorized as biological, environmental, technological, and commercial/regulatory factors.

Biological factors

A number of biological factors have been implicated in the lack of success of bioherbicides. Some factors of the target weed that need to be considered in the early discovery phase are plant architecture and morphology such as presence or absence of leaf hairs and waxy cuticle layer that may be impediments to pathogen infection and retention on the leaf surface (Auld & Morin 1995). These barriers can interfere with the infection process and subsequent disease development that leads to various stages of weed infection and/or mortality. Application of high inoculum rates to the plant have been used to overcome this impediment but these high doses represent application rates and/or volumes that are not practical nor cost-effective. In addition, biochemical plant defense mechanisms, such as phytoalexins, have been known to interfere with the infection of a bioherbicide pathogen, thereby reducing its ability to control the target weed (Gressel 2003). Even the physiological status and age of the plant will have an impact on the pathogen and susceptibility of the plant to the pathogen; this will vary from plant to plant and pathogen to pathogen.

Therefore, detailed understanding of the mode of action and pathogenicity of the potential bioherbicide agent is critical for overcoming these biological factors (Auld & Morin 1995; Bailey 2004; Gressel 2003; Watson and Ahn 2001).

Numerous pathogens and target weeds have been the subject of bioherbicide projects (Charudattan 1991, 2001). It has been postulated that perhaps the wrong target weed was selected for some bioherbicides and that many projects were initiated through the accidental discovery of a disease-causing agent on a particular weed species (Boyetchko & Peng 2004). Further, the target selection should consider the cropping system in which the weed is prevalent and the merits for applying a bioherbicide in specific agroecosystems (Zorner et al. 1993). The discovery and screening of new bioherbicide agents should follow a systematic approach with a clear set of critical traits using appropriate bioassays. In addition, selection of the biocontrol strategy must also be based on the biology and physiology and understanding of the population genetics of the target weed species (Boyetchko et al. 2002). Unlike crops where breeding has led to uniform agronomic traits, weeds are inherently genetically diverse and biotypes of the weed often exist in nature, which may explain the lack of consistent field performance. Conversely, many pathogens have lacked the virulence and/or aggressiveness that are required to cause spectacular efficacy in the field (Evans et al. 2001; Gressel et al. 1996). In addition to high virulence, it has been suggested that rapid infection rates and dispersal are epidemiological characteristics that are critical to the success of the bioherbicide agent (Yang & TeBeest 1992, 1993).

Environmental factors

Temperature and duration of leaf wetness (or dew period) have been cited as the two most important environmental factors affecting the bioherbicide potential of many foliar-applied pathogens, particularly fungi (Auld & Morin 1995; Boyetchko & Peng 2004; Mortensen 1998; Rosskopf et al. 1999). Temperature has been viewed as less critical than moisture requirements, although the interaction between temperature and moisture appears to have a greater effect than temperature alone.

Zorner et al. (1993) suggested that one of the fundamentals of biological weed control is to provide the appropriate ecological conditions that favour the pathogen and thus optimize disease development for effective weed control. Early evaluation of fungal pathogens is often conducted under optimum environmental conditions for infection, usually in excess of 12 to 18 h of continuous dew. However, in the field, these conditions are rarely seen. In addition, laboratory and greenhouse experiments employ application methods that are extreme in that the fungal bioherbicide agent is sprayed till runoff, thereby potentially overestimating the efficacy of the pathogen. Appropriate formulations to overcome these environmental constraints can be utilized to reduce the dependency of these microbial agents on extensive humidity requirements (Auld et al. 2003; Boyetchko et al. 1999; Greaves et al. 1998; Green et al. 1998). Auld and Morin (1995) aptly pointed out that the same environmental constraints limiting bioherbicides also pertain to chemical herbicides and product labels describe the environmental conditions that are optimum or suitable for application of chemical herbicides.

Technological factors

Some of the technological challenges predominantly encountered in the development of successful bioherbicides include i) effective methods for scale-up mass production, ii) formulations and iii) application technology (Auld & Morin 1995; Boyetchko & Peng 2004; Hynes & Boyetchko 2005; Rosskopf et al. 1999; Wraight et al. 2001). Cost-effective fermentation methods have been one reason cited for not pursuing commercialization of a bioherbicide product. The microbe must be mass produced in large quantities as viable, highly efficacious and genetically stable propagules in a cost-effective manner. Submerged (liquid) fermentation has been well developed for the production of bacteria and some filamentous fungi and appears to be highly economical (Rosskopf et al. 1999; Wraight et al. 2001). Both Collego® and DeVine® utilized this method of mass production and their successes have increased the acceptance by industry for this method. Solid-substrate fermentation is highly applicable for mass production of fungi that do not produce spores or other infective propagules readily in liquid culture. However, it is not considered as economical due to other challenges such as higher labour costs, spore harvest, maintenance of sterile conditions and inability to control cultural conditions (Churchill 1982). A bi-phasic system has been employed for some fungi by using liquid fermentation to generate mycelium followed by sporulation using shallow trays that are exposed to various light cycles, depending on the requirement of the microbial agent (Rosskopf et al. 1999). Further, optimization of microbial biomass production requires that a suitable nutritional medium be developed (Wraight et al. 2001). A variety of nutrients from carbon and nitrogen sources, trace elements, and carbon-to-nitrogen ratios will affect propagule yield, stability, and ultimately bioherbicidal activity. Often, these elements must be custom-designed on an individual basis for each bioherbicide agent and low-cost ingredients substituted for the lab-grade ingredients.

Availability and selection of suitable formulations that address critical issues of product stability and shelf-life as well as environmental constraints, indicated above, will have a major impact on the field performance of the bioherbicide (Auld et al. 2003; Boyetchko et al. 1999; Greaves et al. 1998; Green et al. 1998; Hynes & Boyetchko 2005). Formulation ingredients can be used to reduce the rate of evaporation and/or improve the rate of infection of the bioherbicide and increase the moisture-retaining properties. Non-ionic surfactants such as Tween are commonly used in formulations as wetting agents while humectants, oil emulsions and hydrophilic polymers have been used to alleviate the impact of desiccation and reduce the dew period requirement (Auld et al. 2003). Formulations can also enhance the stability, shelf life, and survival of the microbial agent. Germinated fungal spores are also sensitive to desiccation and UV irradiation. Under ideal conditions, a formulation acts as a buffer against environmental extremes that are encountered by the bioherbicide agent, thus promoting disease development on the target weed. This holds true for soil-applied microbial agents as well. Ideally, shelf life of a microbial-based product should be at least one to two years, particularly at room temperature (Auld et al. 2003; Wraight et al. 2001), allowing for production, transport, and distribution of the product. Stabilization of microbial agents in order to extend shelf life has been a major challenge for many bioherbicides, yet more efforts in formulation have focused on the environmental constraints, especially on reducing dew period requirements. Unfortunately, our basic understanding of microbial physiology and techniques for inducing dormancy and stabilizing cellular membranes is not fully understood (Hynes & Boyetchko 2005). Finally, the final product must be formulated in a manner that is safe and easy to use with existing application technology and equipment.

Application technology is an often neglected area that addresses delivery and retention of the bioherbicide propagules to the target weed, whether applied as a post-emergent spray or pre-emergent granule (Boyetchko & Peng 2004). Typical application of post-emergent bioherbicides is through the use of conventional sprayers and by adding a variety of surfactants and adjuvants to facilitate dispersal and retention on the leaf surface (Boyetchko et al. 1999; Boyetchko & Peng 2004). Bacteria, on the other hand, require wounds and natural openings, so cutting and mowing the plants can be employed as a means for gaining entry into the plant. Application of bioherbicides using high water volumes that compensate for low infection have often been used, particularly for early assessment of bioherbicide agents (Boyetchko et al. 2002). Reducing carrier volumes to more practical levels, improving spray retention, and utilization of suitable nozzles to optimize dose transfer that carries the appropriate inoculum load of the active ingredient (i.e. bioherbicide agent) are critical aspects of application that continue to be understudied. In addition, the shearing forces that affect viability of the microbes when applied with conventional spray application equipment are often not considered (Hynes & Boyetchko 2005). These may be overcome through the use of rheology-modifying compounds that preserve the integrity of the emulsified carrier from shearing action. Similarly, techniques for delivery, optimum placement, and equipment for application of soil microbes as pre-emergent bioherbicides need to be evaluated.

Commercial factors

Some of the major commercial challenges that have been cited for the limited success of bioherbicides are market size and cost of production (Auld & Morin 1995). As previously mentioned, products such as Collego® and DeVine® have a small niche market where only one weed is controlled, while commercial development of BioMal® by Philom Bios was suspended because of its limited market size. While Collego® and DeVine® could be readily mass produced, poor cost-effectiveness has deterred commercial availability of a number of bioherbicides. Although Camperico® is used to control only annual bluegrass in golf courses, it is targeted in a high value market. It has been suggested that investment by small to medium sized companies, rather than the multi-nationals, may be the key to developing a viable bioherbicide industry (Auld & Morin 1995; Evans et al. 2001; Watson and Ahn 2001). Smaller companies have lower overhead costs but often lack the capital to invest in biocontrol product development until it is near-market. Even still, the majority of bioherbicides that may be commercialized have been discovered and funded by public institutions. It can be further argued that serious investment in bioherbicide research has been lacking by the agrichemical industry and that potential investors have been noncommittal before they decide to buy-in to a promising bioherbicide product (Charudattan 1991; Evans et al. 2001). Niche market potential and perceived higher product and application costs appeared to be the key concerns of potential investors. Compared to the research dollars invested in the discovery of pharmaceuticals, chemical pesticides, and transgenic crops, the monetary invested in bioherbicides (or microbial biopesticides) has not been as forthcoming (Marrone 1999). With the introduction of lower risk chemicals, competition from chemical herbicides can also be detrimental to a bioherbicide. The merits and benefits of using biological herbicides is in line with increasing public demand for reduced chemical pesticide load in the environment, food safety, ground water contamination, and the development of herbicide-resistant weeds. Furthermore, farming systems, such as organic and pesticide-free crop production require alternative weed control methods and demand for weed control products that are currently not being met by large companies may have a place as minor use products on small acreage crops. Nonetheless, strong partnerships between public research institutions and private companies will be required and a shift from the large industry partner model to small cottage industry or on-farm production model may be necessary (Watson & Ahn 2001).

Enhancement of biological herbicides

A holistic and practical approach that considers the inter-relationship between the bioherbicide agent and bioprocess technologies (i.e. fermentation, formulation, and application technology) is necessary to assure a highly efficacious bioherbicide with consistent field performance (Boyetchko & Peng 2004). These technologies often have influence on each other, therefore, should not be studied in isolation, as distinct or individual technologies, but considered as a continuum. Field performance is used to validate any improvements associated with these technologies, individually and as a "package". Significant advances have been made in the areas of fermentation, formulation, and application technology in recent years. Through incremental and/or major improvements and pyramiding of novel technologies, the performance of biological herbicides can be enhanced. Some recent examples for enhancing bioherbicides are provided below.

Although individual bioherbicides have been shown to have broad-spectrum activity, a "multiple-pathogen approach" that targets several weed species within a particular agroecosystem has been demonstrated (Chandramohan & Charudattan 2001; Charudattan 2001). Use of a fungal pathogen mixture resulted in control of a broad range of grass weed species. The authors indicated that two or more of the pathogens with different modes of action may reduce the risk of resistance to the individual pathogens occurring. This approach can be used for other agroecosystems with multi-weed species and has been demonstrated using combinations of *Phomopsis amaranthicola*, *Alternaria cassiae, Colletotrichum dematium* f.sp. *crotolaria* and *Fusarium udum* f.sp. *crotolariae* for control of pigweeds (*Amaranthus* spp.), showy crotalaria, and sicklepod (Boyetchko et al. 2002). Individually, the bioherbicides controlled their target weed species and, as a multiple-pathogen strategy, controlled several weed species through a single application of the pathogen mixture. The limitation to this strategy may be related to production and regulatory costs.

It has generally been acknowledged that bioherbicides as stand-alone products have been less successful than chemical products. However, bioherbicides should be considered as components of an integrated weed management system and their success will likely rely on their application into production agriculture by combining with other weed control options, including chemical herbicides (Boyetchko & Peng 2004; Boyetchko et al. 2002). Several examples of reduced herbicide rates combined with bioherbicides have reportedly enhanced efficacy (Auld & Morin 1995; Boyetchko & Peng 2004; Boyetchko et al. 2002; Graham 2004; Peng and Byer 2005; Schnick et al. 2002). Tank-mixing or split applications of bioherbicides in combination with chemicals has led to greater weed control than application with the bioherbicide alone, but not all bioherbicides and chemicals are compatible. Application of Collego® with chemical pesticides such as propanil, benomyl, and fentin hydroxide provided evidence that the bioherbicide can be integrated with other crop production practices, while 2,4-D was found to reduce the bioherbicidal activity of Collego® (Smith 1991). Similarly, co-application of *Colletotrichum coccodes* with thiadiazuron led to greater weed mortality than application of the bioherbicide alone (Hodgson et al. 1988) and sequential applications of sub-lethal rates of 2,4-D with *S. minor* resulted in greater mortality to dandelion than the application of either one alone (Schnick et al. 2002). Herbicide-pathogen synergies have also been described by Graham (2004) and Peng & Byer (2005). Virulence of the pathogen *Pyricularia setariae* was enhanced on green foxtail ten-fold when applied with 0.25X label rate of sethoxydim and propanil, thereby resulting in 100% increase in weed control (Peng & Byer 2005). Likewise, control of the perennial broad-leaved weed, scentless chamomile, was significantly improved when the bioherbicide pathogen, *Colletotrichum truncatum,* was applied in combination with synergistic chemicals such as metribuzin (Graham 2004). In some cases, the high inoculum dose of the pathogen normally required for weed control was reduced with the co-application of low rates of the chemical herbicides.

While combinations of chemical and biological herbicides have been explored, some researchers have initiated studies to enhance bioherbicide efficacy in combination with fungal toxins (Vurro 2001). Although fungal metabolites as bioactive molecules have been investigated for use in crop protection, including weed control, they may be used directly or indirectly to enhance bioherbicide performance. For example, ascaulitoxin, a toxin produced by the bioherbicide agent *Ascochyta caulina*, has herbicidal activity against *Chenopodium album*, but combination of the toxin with the fungal organism resulted in a more rapid infection and appearance of disease symptoms (i.e. 1 to 2 days), compared to inoculation with the pathogen only. It was further suggested that increasing the speed of the infection of the pathogen may help to reduce the dependency of the pathogen on lengthy dew periods. Recently, another approach to improve bioherbicidal activity combined a fungal pathogen with a fungal protein, Nep 1, which induces ethylene production and necrosis of several dicotyledonous plants (Bailey et al. 2000a, 2000b). A combination of the Nep1 protein with the pathogen *Pleospora papaveracea* resulted in greater damage to poppy than the application of either treatment alone. In addition, the pathogen *Fusarium arthrosporioides* transformed with the *nep 1* gene was more virulent than the non-transformed pathogen (Gressel 2003).

Enhancement of virulence and pathogenicity may be explored by identifying the genes responsible for virulence, enzyme, or phytotoxin production (Boyetchko et al. 2002; Gressel 2003; Rosskopf et al. 1999). By providing a mechanism for the pathogen to breach the cuticle layer which contains cutin, the infection process of bioherbicide pathogens may be significantly improved. The pathogenicity of fungal pathogens may be altered and thus enhanced by inserting cutinase genes that help penetrate the aerial part of the plant host. For example, the pathogenicity of *Alternaria cirsinoxia*, a pathogen of Canada thistle, was enhanced due to acceleration of fungal infection of the leaf cuticle (K.L. Bailey, Agriculture and Agri-Food Canada, personal communication). Disease development was also more rapid in the transformed strain of *A. cirsinoxia* than the wild type strain. This may have been due, in part, to larger lesion size and greater infection efficiency exhibited with the transformed strain of the pathogen (Bailey 2004).

Research initiated at Montana State University is exploring the potential of pathogens that overproduce and excrete amino acids that are inhibitory to the growth of plants (weeds) (Sands et al. 2001). It may be possible to enhance virulence using these pathogens or their variants that demonstrate this capability of amino acid overproduction that can interfere with protein metabolism. For example, valine, leucine, and isoleucine regulated the activity of acetolactate synthase (ALS) and overproduction of isoleucine by a particular bacterial strain led to a decrease in ALS activity in tobacco. Similarly, a variant of the pathogen *Fusarium oxysporum* f.sp. *cannabis* was found to overproduce valine, an amino acid that inhibited growth of *Cannabis sativa*. The wild type strain of the pathogen only provided 25% control of *C. sativa*, while the variant known to overproduce valine was more virulent than the wild type and provided 70 to 90% control.

Since the first introduction of Collego® and DeVine® as simple aqueous suspensions, a variety of formulation ingredients have been investigated to alleviate the environmental challenges that have limited bioherbicide success (Auld et al. 2003; Boyetchko et al. 2002). Simple oil emulsions with vegetable oils such as canola, corn, peanut, safflower, soybean, and sunflower led to improved water retention properties and leaf wetting properties, but enhanced efficacy was not necessarily observed. Invert emulsions consist of a water-in-oil entrapment mixture in which the microbial bioherbicide is contained within the aqueous phase. Although this type of formulation has reportedly reduced evaporation of droplets and thus the dependency of bioherbicides for extensive dew periods, the high oil content is known to have phytotoxic effects on nontarget plants. Recently, a water-in-oil-in-water (WOW) formulation was described where the water held in oil is in a continuous phase of water that contains the fungal pathogen (Auld et al. 2003). The WOW can consist of 1 to 5% oil and the types of oils, surfactants, and emulsifiers are infinitely possible. Auld's group reported that the dew dependency of *Colletotrichum orbiculare* was significantly reduced as a result of the WOW emulsion.

Liquid formulations have commonly been used for bioherbicides, particularly since the majority of bioherbicides have been foliar-applied or post-emergent in nature. Solid-based formulations have been used, predominantly for target weeds where infection is at or below the soil surface. A type of granular formulation that has been explored for fungal bioherbicides is based on the entrapment of fungal propagules in a wheat-gluten matrix (Connick et al. 1991). Daigle et al. (2002) have further expanded the utility of the pesta to entrap bacteria applied as pre-emergent bioherbicides for annual grass weeds. Semolina flour has been replaced with oat flour and application of the pesta-formulated bacteria has provided up to 85-90% control of green foxtail in the field. 'Stabileze' is another solid formulation that is based on a water-absorbent starch mixed with sucrose, corn oil, and silica (Quimby et al. 1999). It is a simple method for granulating fungi where sucrose appears to be the most important factor for improving viability and stability of the fungi. The 'stabileze' can also be used for bacteria, but in a form where the formulated organisms are re-suspended and applied for post-emergent application, not to soil (Zidack & Quimby 2002). Additional research to modify the 'stabileze' is required because the suspension must be diluted a hundred-fold before it is sprayable, resulting in a reduction of the titre of active ingredient.

Research in formulation of bioherbicides is a continuous process and several advances have been made. The biology of the target weed and the individual traits of the bioherbicide agent will pre-determine the most appropriate type of formulation and delivery method. Greaves et al. (1998) stressed that the success of the next generation of bioherbicides will be determined by novel developments and applications in formulation technology.

Summary

Weed control methods in modern agriculture have not led to the eradication of weeds, in part, because the genetic diversity of weed populations allow them to thrive and adapt to various agroecosystems, environmental changes, and chemical herbicides (Buhler 2002; Harker & Clayton 2004). Therefore, weed management systems must also be diverse with a focus on strategies that employ multiple weed control methods, as opposed to single or stand-alone control measures such as that offered by chemical herbicides. In addition, long-term weed population management should be the objective, rather than immediate weed eradication (Harker & Clayton 2004). Biological herbicides have tremendous potential as a weed control strategy but they have often been neglected due to their own set of shortcomings. The commercial industry model for the development of the early prototype bioherbicides generated a great deal of interest in their use as additional products to chemicals. However, the perception that biological herbicides were possible replacements to herbicides led to the unrealistic expectations that they were another silver-bullet for weed management (Charudattan 2001; Evans et al. 2001). Some of the early features expected for biological herbicides still hold true: high and consistent efficacy, host-specificity, serve a market need, ability to economically mass produce and formulate, and ease of application. However, these features alone will not determine the success or failure of biological herbicides.

Critics and sceptics could argue that the lack of many more biological herbicides in the marketplace proves that they cannot deliver the goods and are thus a failure. Some counter-arguments are that the level of resources dedicated to traditional weed control technology has not been as generous for biological herbicides and that lack of investment and diminishing resources for research have resulted in less rapid progress in this area. The early successes of bioherbicides such as Collego® and DeVine® provided the impetus for further bioherbicide research, but lack of knowledge and advances in a variety of technologies such as fermentation, formulation, and application technology have not facilitated many other biological herbicides to progress beyond the early evaluation phases. Certainly, a better choice of strain selection, as well as target weed selection is required. Use of multiple pathogen strategy can expand the number of weeds controlled through a single application or synergy with chemical herbicides or microbial toxins can be used to enhance efficacy. Manipulation of the virulence and/or pathogenicity factors to enhance bioherbicide efficacy can also be exploited, but genetic engineering of bioherbicide pathogens may be a difficult concept to sell, given the current climate of using molecular technology in crop protection. Inconsistent field performance has often contributed to lack of success of bioherbicides, and the causes could be attributed to a variety of biological and environmental factors. Significant advances in technology development for fermentation and formulation in recent years have provided better tools to overcome these constraints and enhance efficacy in the field. It should also be recognized that early field evaluation is not conducted with a "final" bioherbicide product, as with chemical herbicides, but that many of these biological herbicides are field tested at various stages of development. But their field performance comes under high scrutiny nonetheless, because they are a relatively "new" technology that has yet to be widely accepted.

Some of the weak links for improving biological herbicides are related to our understanding of weed biology, physiology, and ecology, fundamental agronomy concepts for application into crop production, and integration with other weed control strategies that form the basis for IWM. Teams of researchers in many facets of weed management and agronomy are required to implement biological herbicides into crop production systems, but these teams must be further strengthened in biological herbicide research. Bioherbicides are not stand-alone technologies, but need to be applied as complementary weed management tools in an IWM package (Hurle 1997). Simplicity and ease of use of chemicals have been used as a quick-fix for weed management, but we all have a responsibility as environmental stewards to utilize chemicals and other weed control options judiciously. While IPM has been well accepted for insects and plant diseases, it has been suggested that IWM is still at an early stage of development (Buhler 2002). Furthermore, given the current economic reality, it may be necessary to re-think how we delivery these bioherbicide technologies. To build a viable bioherbicide industry, the probability of success may be higher with small to medium sized enterprises, including cottage industry or on-farm production models to which the market size is more justifiable. Concerted efforts to incorporate biological herbicides as part of an IWM package, using expertise in diverse areas of weed science, are required to ensure that they are adopted as an additional weed management tool.

Acknowledgements

I wish to thank Drs. Gary Peng and Russell Hynes from Agriculture and Agri-Food Canada, Saskatoon, for their thoughtful discussions and review of this manuscript.

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Risk reduction and stewardship, perspectives for herbicide use

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CropLife Canada is the trade association representing the developers, manufacturers, and distributors of pest control products. This paper reviews the risk reduction practices and extensive and rigorous science review prior to the commercialization of all pest control products, as well as the various stewardship initiatives undertaken by the industry. The environmental and economic benefits of herbicides are addressed. Food and fibre production would be negatively impacted without the use of herbicides, through increased yield loss and the resulting increased production cost. Environmental consequences of increased land use to meet human demand for food and increased soil loss are also discussed. The crop protection industry is committed to supplying tools that meet not only pest management needs but society's need for environmental preservation and agricultural sustainability.

Introduction

CropLife Canada is the trade association representing the developers, manufacturers, and distributors of plant science innovations – pest control products and plant biotechnology – for use in agriculture, urban and public health settings. The mission of CropLife Canada is to support sustainable agriculture in cooperation with others, by building trust and appreciation for plant life science technologies.

CropLife Canada and its member companies are major supporters of risk reduction, stewardship initiatives and technologies for sustainable agriculture, forestry and urban pest management. This is accomplished as individual companies as well as through the industry association. Each company is focused on providing pest management tools which control pests without having a negative impact on human health or the environment. As an association, CropLife Canada member companies introduced industry-led voluntary initiatives to ensure a "cradle to grave" approach to stewardship and risk reduction. Under the banner *stewardshipfirst** these initiatives encompass the entire product life cycle. The importance of these initiatives (*see appendix 1 on stewardshipfirst**), is demonstrated by the fact that two-thirds of CropLife Canada resources are devoted to *stewardshipfirst** initiatives.

This paper is intended to provide a summary of the industry activities and positions on risk reduction and stewardship in relation to herbicide use.

Industry's role

Industry's role in the development of crop protection products can be categorized into four primary areas: Discovery, Hazard Characterization, Definition of Environmental and Economic Benefits, and Risk Assessment and Registration. The process, for each new product, on average, requires nine years to complete (from discovery to commercialization) which represents a 10% increase from 1995. (Ref: 2003 Phillips McDougall Report, commissioned by CropLife America and the European Crop Protection Association from CropLife Europe). Between discovery and registration, a chemical goes through a series of "stage gates" where risks and benefits are assessed by the company. Many products are eliminated through this stewardship process. The average cost for each new product is $184 million (US). Due to the stringent requirements, only one in 140,000 chemicals synthesized makes it from discovery to commercialization and only 50% of chemicals in development make it to commercialization.

The ultimate objective is to provide pest control products that control pests without causing harm to human health or the environment. In order to satisfy this objective, industry aims to find solutions that are target specific and can be used safely. The industry promotes the safe and responsible use of pest control products through partnerships with growers, industry, educators and regulators. The *stewardshipfirst** initiatives are one means of communicating responsible product handling and use to our partners.

In order to put "Reduced Risk" in context, the various risks posed by the use or presence of pest control products to health and the environment must first be quantified. "Risk" must be differentiated from "hazard". Hazard is relatively easy to quantify, but risk definition can only be conducted with a full understanding of the exposure of the test system to the substance under investigation.

Discovery

Discovery represents the identification and creation of molecules, which include natural and synthetic, as well as synthetic copies of natural molecules with pesticidal properties. The discovery phase represents a screen of a large volume of molecules targeted at specific plant biochemical mechanisms as well as including an initial health and environmental hazard screen.

Products continue through this process and on into *risk characterization* with a focus on the following characteristics:

- selective in their action;
- effective at low rates;
- bio-degradable;
- safe to the consumer;
- safe to the environment;
- safe to the user

Good agricultural practice (GAP)

Once a product has been identified that is effective in controlling a specific pest (or group of pests), efficacy studies are carried out over several years to determine the lowest rate that can achieve effective and consistent control of the pest. It is vital to identify this rate as all risk assessments will be based on the rate of application. It is one of the most important ways that companies can reduce risks involved with the product.

Risk assessment

Companies conduct defined, scientific studies in accordance with Good Laboratory Practice Standards. These studies must be conducted following protocols which are defined and accepted by OECD (Organization for Economic Cooperation and Development), an international body of scientific experts representing various governments, including Canada, around the world. The risk assessment consists of a wide variety of study disciplines including basic chemistry, mammalian toxicology, animal metabolism, occupational exposure, plant metabolism, crop residue, environmental fate, environmental toxicology and agronomy.

All hazard data from the toxicology, chemistry and metabolism studies are looked at together and “risk” is defined as the inherent toxicity or hazard of the substance in relation to the exposure one has to it. That is,

RISK = HAZARD x EXPOSURE

As discussed in more detail below, through conducting the various hazard/toxicity studies, health and environmental characteristics are identified and recommendations on best management practices (exposure) are made which serve to minimize risk.

Risk assessments are conducted for routes of potential exposure to the substance and include:

1. **Health risk assessment:**
   - Dietary- food & water (consumer exposure)
   - Occupational and Bystander (user exposure)

2. **Environmental risk assessment,**
   - Non-target organism exposure
   - Fate in the environment

Registration

Not only do companies conduct risk assessments throughout the development of a product, but risk and value assessments are also conducted by national government regulatory agencies prior to commercialization. These regulators must be satisfied that the product can be used safely prior to the government granting a registration for commercialization. Governments use the precautionary approach. In Canada, the Pest Management Regulatory Agency (PMRA) of Health Canada is the pesticide regulatory authority. Similar to the other sophisticated pesticide regulatory agencies throughout the world, the PMRA follows a rigorous, science based risk assessment process. This process includes consideration of post registration monitoring, enforcement activities and compliance to ensure products are used in accordance with labels.

Health risk assessment

In the health risk assessment, the hazard or toxicity of each specific substance is first defined or identified under various situations. This entails identification of the toxic end points or adverse health effects using a wide variety of test species as the model – from cell cultures to mammals. These toxicology studies are conducted to assess possible effects on humans and animals and include: acute, short term, long term, cancer, genetic, neurotoxicity, reproductive (including endocrine disruption), and effects on pre/post natal. The studies are conducted to assess the hazard through various routes of exposure (i.e. ingestion, contact and inhalation). Uncertainty factors are used in the risk assessment. A ten-fold safety factor is incorporated to account for extrapolation from animals to humans and an additional 10-fold safety factor to account for variation within the human population. Therefore there is a minimum of a 100-fold safety factor applied to the dose which is defined as causing **no** adverse effects in animals.

The exposure assessment not only assesses the risk of each use but also conducts an aggregate risk assessment. This aggregate assessment considers exposure from all food residues, drinking water, and other non-occupational exposure sources such as those arising from use in and around homes and schools; thus combining multiple pathways and relevant routes of exposure. Each subpopulation (eight are defined including infants and children) is considered in the assessment.

Cumulative Impact (common mechanism of toxicity) is also in the process of being introduced into the risk assessment process by the regulators. A Cumulative Risk Assessment considers the potential combined health effects resulting from exposure to pesticides with a common mechanism of toxicity.

Mitigation measures are developed in response to the nature of the potential risk, to user or to consumer. These measures are translated into label use instructions. For example, measures to mitigate risk due to short term inhalation toxicity for a user could be expressed on the label as a precautionary statement, such as “wear a respirator”.

Environmental risk assessment

The characterization of environmental risk follows essentially the same process as for health risk characterization. It includes definition of the hazard to species or processes of interest, and an assessment of the potential for exposure based on the intended use and environmental conditions. Mitigation measures are developed to ensure an adequate margin of safety to non-target organisms and ecosystems.

Hazard is identified through the results of studies conducted on various representative species including:

- Earthworms
- Bees/Pollinators/Predators/Parasites
- Freshwater invertebrates - water flea
- Marine invertebrates – shrimp, shellfish
- Fish
- Birds

- Mammals
- Non-target plants:
  - Fresh water algae
  - Marine algae
  - Terrestrial plants
  - Aquatic plants

Studies are conducted to represent the duration of likely exposure (i.e. acute/short term/chronic/reproduction), route of exposure (i.e. oral, dermal, inhalation), and life stage (adult, juvenile, full life). The original compound and relevant breakdown products are tested. The active ingredient alone and/or the formulated product is tested.

Exposure is assessed through studies that define the fate (physico-chemical properties, persistence/transformation, mobility) of the substance or products, taking into consideration the intended use pattern.

In the study of the environmental fate of a substance, both laboratory and field studies are required. These studies define the chemical properties and measure the interaction with soil, air, sunlight, surface water, and ground water. The environmental fate essentially defines how the product behaves in the environment and ultimately its impact on plants and animals in relation to the hazard.

Physico-chemical factors of each product are considered in the following laboratory studies:

- Solubility (water, organic liquids)
- Hydrolysis constant (K_H): rate of breakdown in water, at various pH's
- Photolysis constant (K_P): breakdown by light in soil, water, air
- Vapour pressure (mPa): capacity to volatilize
- Henry's Law Constant (HC): air-water partition coefficient
- Octanol/water partition coefficient (K_{ow}): preference for oil or water; bioaccumulation
- Acid dissociation constant (pKa)

Environmental Fate studies also include:

- Biotransformation (20 -30 °C)
- Aerobic and anaerobic soil and water/sediment
- Sorption coefficient (K_d)
- Organic carbon sorption coefficient (K_{oc})
- Soil half-life; time in days to decline
- Field dissipation: soil and aquatic half-lives (DT_{50})

- Accumulation: rotational crops, fish, aquatic organisms
- Mobility (water, air)
- Post commercialization monitoring

All routes of dissipation are considered in the exposure/fate characterization (See Figure 1).

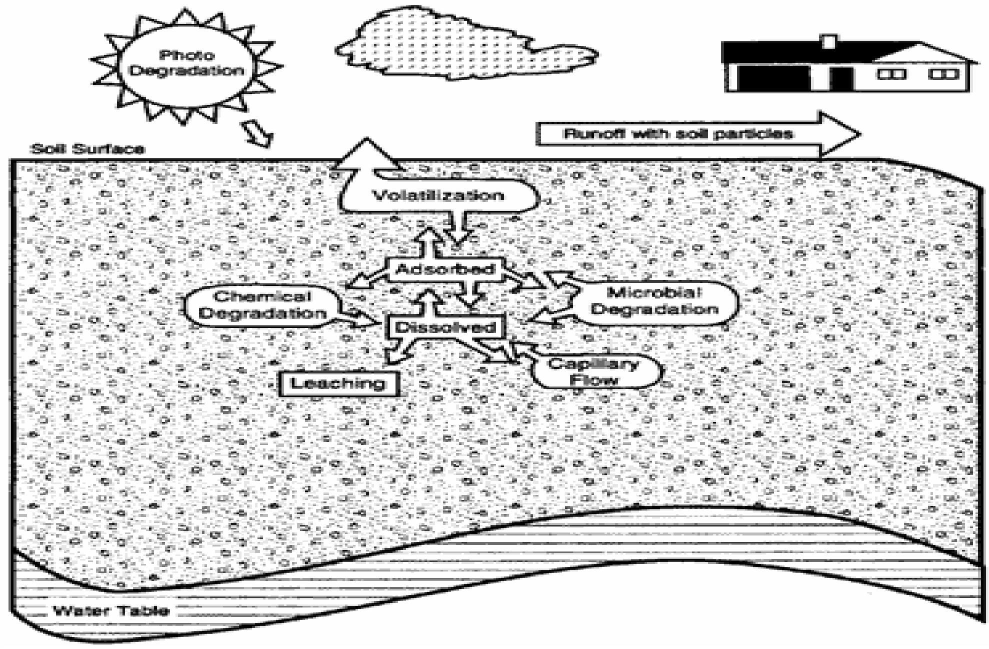

Figure 1: Potential routes of pesticide dissipation in the environment.

Environmental risk assessment is a complex discipline utilizing hazard and toxicity data on the compound in question, as well as data on the fate of the substance in the environment under specific environmental conditions, and farm practices in relation to the use pattern.

Some of the questions that must be answered in order to complete the risk characterization include:

- What happens to the pesticide in soil, water and air?
- How do pesticides move in the environment?
- How do pesticides get into the atmosphere?
- How do pesticides get into ground and/or surface water?

- What happens under practical use conditions?
- How fast and by what means does it degrade?
- What are the breakdown products, and are they biologically active?
- Are the breakdown products mobile in water or air; how far will they travel from the application site? Will they accumulate in the environment?

Again the Risk Assessment Equation becomes very important.

RISK = HAZARD x EXPOSURE

Once the risk is defined, various measures can be put into place to mitigate risk under specific conditions. These will serve to avoid any undue risk in the use of a product and are addressed on the product label. Similar to the health risk assessment and mitigation, there is little value in communicating values from the hazard assessment in isolation. Label use directions and precautions present the results of these risk assessment analyses in instruction form for the user.

CropLife Canada members support and encourage the use of Environmental Farm Plans (EFPs) and the use of Best Management Practices (BMPs). This includes establishing buffer zones, farmable berms, terracing, etc. in higher risk situations.

Environmental and economic benefits

Risk is the possibility or probability of adverse consequence. All activities in which we participate carry a certain element of risk. However, risk is accepted at some level to obtain a benefit where the benefit outweighs the risk.

Therefore risk should always be considered in relation to benefit.

Examples of benefits afforded through the use of pest control products include:

1. Protection/production of food and fibre by ensuring a safe, abundant, affordable food supply;
2. Effective use of resources (agriculture, forestry) through increased production from the same or less land;
3. Health protection - disease prevention through the control of insect vectors (West Nile virus, malaria);
4. Urban landscape maintenance in gardens, parks, sports fields;
5. Preservation of natural habitats by control of invasive alien species.

A recent US study conducted by the National Center for Food and Agricultural Policy, Washington, U.S. attempts to quantify the benefits of herbicides and explores various scenarios. (Note: NCFAP is a broadly funded organization with considerable funding from grower organizations.) They determined that without the use of herbicides an additional seven million hand weeders would need to be employed by farmers, or an increase in cultivation would need to take place. The latter would have a negative effect on soil erosion and soil compaction, essentially negating the environmental benefits of reduced tillage practices. It is currently estimated that no-till practices result in the prevention of 304 billion pounds of soil erosion annually. Production would be expected to decline by 21% (288 billion lbs of food/fibre), and result in a $ 7.7 billion (US) increase in production cost. The value of lost production is estimated as $13.3 billion. Coupled with the increased production cost, this results in an estimated $21 billion reduction in grower income, representing 40% of the current total.

Herbicides cost on average $30-50/ac vs. $700/ac labour. With regard to herbicide non-use and replacement with alternatives, an additional 70 million workers would be needed in the U.S.

Conservation Technology Information Center, Lafayette, IN, U.S. (www.ctic.purdue.edu) has attempted to quantify conservation tillage benefits. They identified that the alternatives to herbicides would present significant societal, environmental and economic issues of their own. Conservation (minimum/no) tillage has enjoyed significant growth due to the introduction of herbicide tolerant crops (38% or 109 million ac (US)).

There has been increased adoption of reduced tillage practices with the introduction of herbicide tolerant (HT) crops (an increase of 35% since 1996).

Other benefits to conservation tillage practices identified by CTIC include:

- Reduced soil erosion (1 billion tons/yr)
- Reduced sediment (aquatic habitat, $ 3.5 billion savings (water treatment, navigation))
- 309 million gallons fuel/yr (1 billion lbs of CO_2)
- Ecosystem habitat improvements
  - –Earthworm populations + 6X
  - –Quail food sourcing 1/5th time
- Organic matter improvement
- Soil moisture increases (2-4”/yr)

Registration

The Registration of a product represents the end result of the risk and value assessments. Registration is granted by the regulatory authority and defines the conditions of use for a product and represents the “license to sell”.

All registrations are subject to periodic review (every 15 years or earlier) in relation to new information and evolving scientific standards.

The future

Thanks to advances in agricultural technology, total food production has largely been able to keep up with global demand. Maintaining the balance will be challenging as population growth outstrips land and water availability. Although organic farming offers consumers in affluent countries an additional choice, it is not a viable solution for feeding an ever-increasing world of an essentially urban population.

CropLife Canada actively promotes the use of Integrated Pest Management (IPM) practices to provide the best social, economic and environmentally sustainable solution.

Summary

Caution must be used when using Reduced Risk terminology. It is a relative term, and must not be confused with hazard, or exposure alone. Various factors or situations and use conditions can significantly influence the risk or safety of a product and its use. All products registered for use today should be considered low risk due to the precautionary approach in the science of risk assessment, the intense regulatory oversight, and the various stewardship initiatives.

It is important to look at sustainable agriculture as a whole by achieving an economic, social and environmental balance and considering the whole farm and land management approach. Each scenario has its own assessment of risk, and associated mitigation measures. CropLife Canada and its members are committed to continuing to provide pest management tools to support sustainable agricultural practices.

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Appendix 1. Stewardshipfirst*

Weed science at the crossroads

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As world markets for herbicides grew exponentially during the latter half of the twentieth century, weed scientists focused mainly on evaluating the efficacy of new compounds and understanding their mode of action, or on determining crop losses due to weeds. Unlike their counterparts in plant pathology and entomology who devoted comparatively more research effort toward studying the life habit and ecology of diseases and insects, the majority of weed scientists focused primarily on control as the priority. Currently, with world-wide herbicide usage remaining nearly constant from one year to the next, a progressive increase in the occurrence of herbicide resistant weeds, and changing public attitudes toward the use of pesticides on food crops and in the environment, weed science is now at a crossroads with signs pointing in two directions. One points toward the imperative of positioning weed research within the broader context of integrated crop and weed management systems at a landscape scale; the other toward functional genomics as a means of understanding and potentially exploiting the underlying mechanisms that are inherently characteristic of weeds or that confer a competitive advantage to crop plants. Weed scientists must extend beyond their traditional disciplinary boundaries, not only in forging collaborations with scientists from outside the discipline, but in conducting novel research that is meaningful to agricultural producers on the one hand, and to those in the 'purer' disciplines of plant biology and ecology on the other. This, in turn, will enhance the status of weed science, a simple measure of which will be an increase in impact factors of journals such as Weed Science and Weed Research among journals relating to agronomy, plant science and ecology.

Introduction

Weed science as we have come to know it over the past 50 years had it's origins in an Erlenmeyer. The science, like many of its practitioners in the latter half of the twentieth century, was conceived at the end of the Second World War and was born from the discovery of the phenoxy herbicides. Agriculturalists, like most of society, embraced the wonders of this and other inventions, gizmos and concoctions, including plastics and new medicines and subscribed firmly to the belief in "Chemistry for a Better Living".

Following the discovery and proven utility and profitability of phenoxy herbicides for broad-leaf weed control, the agricultural chemical industry burgeoned such that markets for herbicides grew by an astounding 6.3% per year through to the early 70's, largely through wide scale adoption of the substituted ureas and triazines in both Europe and the USA (Kudsk & Streibig, 2003).

In Canada, particularly in western Canada, markets grew rapidly during the late '70's and 80's with the expanded use of glyphosate in minimum and no-tillage systems, commercialization of the extraordinarily effective 'fops' and 'dims' for grass weed control, and the development and quick adoption of the sulfonylureas and imidazolinones.

These were lively times, during which the majority of public-sector weed scientists were either conscripted by the agrichemical industry as co-developers of new products or responded to the interests of farmers who readily embraced the technology and were asking their own questions about product compatibility, use of adjuvants, potential for carryover, effects of weather, and when and what to spray.

With few exceptions, most weed scientists had a fascination, preoccupation or even an infatuation with herbicides. As a badge of belonging, both farmers and weed scientists had collections of hats of all colours embroidered with names like Carbyne, Eradicane, Torch, Amitrol T, Bladex and Mataven.

These were the years when one might facetiously describe many weed scientists as those whose "science" required them to have an working knowledge of how to do a dilution series, an ease at laying out trials in randomized complete block designs, and the ability to subjectively score both crop tolerance and weed control on a scale of 0 to 9. In some cases these same people or their colleagues were adept at using radiotracers to elucidate the uptake, transport, and metabolism of chlorophenoxy, dioxy u-namit in a) soybean b) wheat or c) rapeseed and a) velvetleaf b) Tartary buckwheat or c) wild oat in a quest to understand the basis of herbicide selectivity. This was the time when the title "weed physiologist" had a particular cache and when the terms μCi/mg, lyophilized enzyme preparation, thin-layer chromatography and liquid scintillation spectrometry had great currency.

So through most of the 1960's, '70's and '80's weed science was mainly herbicide driven. This is reflected in the fact that during these years most published articles in the weed science literature pertained to herbicides (Kropff & Walter, 2000). Not only were most undergraduate courses in weed science offered at that time mainly focused on herbicide mode of action and factors affecting herbicide performance, but at many universities the sole graduate course in weed science was on the physiology and biochemistry of herbicides.

Times and circumstances have changed. For one thing, the herbicide market has matured and world-wide annual growth is about 0.1% (Kudsk & Steibig, 2003). Since the mid-eighties there has been ongoing consolidation in the crop protection industry and fewer new products with novel active ingredients entering the marketplace. Whatever happened to Gulf, Velsicol, Amchem, May and Baker, Ciba Geigy and even Hoechst for that matter? And for those who have not kept current with consolidation in the industry over the past 10 years, what or who is Arysta anyway?

In addition to maturation of the market, Kudsk & Streibig (2003) attribute the abatement in new product development to the following:

1. the “easy” chemistry has largely been exploited,
2. the registration of new compounds requires increasingly comprehensive (and costly) submissions on both toxicology and ecotoxicology, and
3. the introduction of herbicide tolerant crops has completely changed the herbicide market and the focus of the agrichemical industry.

The first point implies that the pipeline has begun to dry up and that by screening countless thousands of chemicals, the agrichemical industry has serendipitously identified all, or the majority, of active compounds.

The second point reflects a shift in societal values and a growing public concern over the use of pesticides since the 1980’s. Society no longer fully embraces the notion of “Chemistry for a Better Living”. With refinements in chemical detection methods, concerns about chemicals in the environment, and a growing belief that the integrity of our food supply is compromised by the use of pesticides, public attitudes have changed. This, in turn, is reflected in more stringent regulations governing the registration and use of pesticides, and a shift in primary regulatory responsibility in Canada from Agriculture and Agri-Food Canada to the Pest Management Regulatory Agency of Health Canada.

The third point is one to which most weed scientists are highly attuned. It reflects a change in focus of many of the major industry players – away from the development of new compounds to an investment in the seeds and biotechnology sectors and a corresponding change in the name of the industry association in Canada from the Crop Protection Institute of Canada to CropLife Canada.

The reduced interest in new product discovery was driven home in a lead story published in late 2003 in the Western Producer headlined “Monsanto ties future to biotech crops”. The article reports on a reduction of 39 jobs in Canada, and a 7 to 9% reduction in the company’s global workforce. According to one analyst, the seed and biotech segment of Monsanto’s business accounted for 39% of company’s earnings in 2003 compared to 6% the previous year. Implicit in this is a reduction in the profitability of its agrichemical sales, largely related to a decline in world demand for Roundup. A spokesperson for the company is quoted as saying “While the company will continue to support and sustain its agricultural chemical division, it won’t expand work in that area. It’s a declining sector”.

So, on the one hand, the momentum behind the pesticide industry has waned significantly in the past 20 years or so - and with this, much of the hype and excitement associated with the unveiling of new chemistry. At the same time, there has been a concomitant realization that production agriculture has developed an over-dependency on chemicals over the past 30 years. The latter has manifested itself in numerous ways, not the least of which is the widespread occurrence of herbicide resistant weeds. These factors combined have prompted a re-thinking of the role of weed scientists, the approaches they take in practicing their craft, and the kind of science necessary to advance the discipline. Following from this, numerous authors including Hall et al. (2000) have begun to redefine the future directions for weed science.

Signpost 1: IWM this way

Foremost among the changes is a move toward the development of integrated weed management (IWM) systems. Conceptually, this has considerable appeal and if effectively implemented, undoubtedly will resolve certain of the problems associated with near-complete reliance on herbicides for weed control. Experience has shown, however, that even where good information exists, mainstream producers are reluctant to adopt novel IWM practices as a substitute for herbicides unless they are confronted with cataclysmic failure of conventional technologies that leaves them with no alternative. Such is the case in Western Australia where the widespread occurrence of multiple herbicide resistance has severely limited the fit of herbicides within the production system and prompted more ready acceptance of IWM practices (Llewellyn *et al.*, 2004).

Compared to entomologists' knowledge about insect pests or plant pathologists' knowledge about diseases and host-pathogen interactions, weed scientists are much less knowledgeable about the basic biology and ecology of weeds, or how they interact with crop plants and the environment. Weed science is seen to have lagged behind other disciplines in supporting the development of IPM practices (Mortensen *et al.*, 2000). This is attributed to differences in origins of the disciplines, with the study of weeds only becoming recognized as a "science" with the advent of herbicides which then lead predominantly to a control mentality. Previously the study of weeds fell within the domain of agronomists, horticulturists and botanists. This contrasts with the other disciplines which were established in their own right by the beginning of the 20th century and whose practitioners devoted major attention toward understanding the taxonomy, reproductive behaviour, host specificity, biology and ecology of the species. Until quite recently, for many weed scientists such things as the mating systems of weeds and other basic biological characteristics were seen either to be of only cursory interest or largely irrelevant.

Two elements that underpin the concept of integrated weed management are 1) the use of multiple control tactics and 2) the integration of knowledge about weed and crop ecology into the management systems in such a way to diversify selection pressures and reduce environmental degradation. Recent review articles by Buhler *et al.* (2000), Mortensen *et al.* (2000) and Buhler (2002) expand on the topic of integrated weed management and point to the challenges that confront weed scientists in understanding the complexities of dealing with multiple species with a diversity of life history traits.

As much as anything, the occurrence of weed resistance has propelled integrated weed management research and underscored the importance of knowing more about the basic biology and ecology of weeds including information about mating systems, out crossing rates, pollen flow, population genetics, fecundity, seed dormancy, seed bank dynamics, seed longevity and dispersal mechanisms. At the same time, it has compelled both farmers and weed scientists to contemplate ways of controlling or managing weeds by diversifying or destabilizing the system, and by reducing selection pressure by reducing herbicide use.

One of the hallmarks of IPM for control of insect pests is the use of economic thresholds in determining whether or not an outbreak warrants pesticide treatment. These are supported by bioeconomic models that typically relate the severity of pest populations to projected crop losses, costs of control and economic returns. While a number of such models have been developed by weed scientists, uptake by farmers has been limited (Wilkerson *et al.,* 2002*)*. The current consensus is that the concept of thresholds and the application of models that typically define the effects of one, or sometimes two, weed species on crops are most useful as educational tools.

A limitation of current models is that they generally do not factor into account the consequences of seed rain on future weed populations and in this respect are not holistic in nature. One of the few economic optimum threshold models that has been developed and that calculates the long-term costs associated seed production indicates thresholds are in the order of 4- to 7-times lower than economic thresholds based solely on yield losses (Buhler, 2002).

Despite current limitations, O'Donovan (1996) argues in his paper "Weed Economic Thresholds: Useful Agronomic Tool or Pipe Dream", that the use of models will support more rational and objective approaches to weed management and that constraints of the current models can be overcome in the future by the use of more realistic sampling procedures to assess the impact of weeds over large areas, by placing more emphasis on the effects of the crop on weeds rather than weeds on the crop, and by greater coordination among weed ecologists in establishing standard protocols for long-term studies. Wilkerson *et al.* (2002) concur.

Forestry's EMEND project as a model

For agroecological studies the current imperative is to draw together a broadly based team to work on large-scale, landscape based programs. There are intriguing models that we can learn from, one of these being the EMEND Project in Forestry (http://www.biology.ualberta.ca/old_site/emend/).

EMEND stands for Ecosystem Management by Emulating Natural Disturbance. It is a project that was conceived by two entomologists but grew to include a host of other experts representing at least 10 disciplines, ranging from conservation biology through soil biogeochemistry and hydrology, through silviculture and forest measurements, to economists and sociologists. The EMEND

Project consortium consists of two principal corporate partners, the Canadian Forest Service, a provincial ministry, an institute and at least five universities. It is the world's largest, replicated, single site, managed forestry experiment and is situated in northern Alberta near Peace River.

In a letter supporting the nomination of the EMEND Project for an award, a noted authority from the United States Department of Agriculture Forest Service wrote that "the EMEND research project is extraordinary because it is so innovative, and so comprehensive that it has become internationally acclaimed, and serves as a model system for rigourously testing hypotheses about the impact of alternative forest management practices on the ecological integrity and the long-term sustainability of forested landscapes."

Clearly there are differences between forestry and farming, but nevertheless imagine the same thing applying to an agricultural landscape. Imagine a reviewer that would pen "the Agroecological Research Project is extraordinary because it is so innovative, and so comprehensive that it has become internationally acclaimed, and serves as a model system for rigourously testing hypotheses about the impact of alternative agricultural management practices, including weed management, on the ecological integrity and the long-term sustainability of rural landscapes".

The beauty of the EMEND Project is that a series of independent but interconnected research projects is being superimposed on a grand experimental design. This, then, provides a unique opportunity for the investigators to not only identify the major treatment effects but to understand many of the interactions that characterize a very complex system.

Can such an approach be applied in agriculture? It's my belief that it could, most probably on a watershed scale. Already there are a number of watershed management organizations that band farmers together with researchers. With the proper incentives and with the right leadership perhaps these organizations could emulate the EMEND Project in developing a comparable "Agroecological Research Project". Could this be championed by a weed scientist? By all means! Just as the EMEND Project leaders are entomologists, an "Agroecological Research Project" of a similar scale could be lead by weed scientists.

Without contextualizing weed research as part of a broadly based study of agroecosystem management, much of what is currently defined as weed biology and ecology might well be a misspent effort. It might constitute good botany, but may be questionable weed science.

In addressing the role of ecology in the development of weed management systems, Mortensen *et al.* (2000) identify a number of common attributes of weed ecological research that will benefit cropping systems design and performance. Chief among these is the imperative that such research be seen in the context of an integrated crop management system. The authors conclude that invariably this will involve the need to engage experts across a broad range of disciplines, with applied researchers, i.e. weed scientists, taking the lead in building teams that include both non-traditional players as well as primary producers. Only then will the knowledge generated from the research become transformational, as opposed to transactional which characterizes much of the science today.

Signpost 2: The new science of genomics

As one sign points to research supporting IWM based on an ecological approach to weed management, another points to the necessity of weed scientists to capture opportunities arising from major advancements in molecular biology and genomics.

Genomics refers to the complete or nearly complete characterization of all genes in an organism with functional genomics describing the relationship between specific genes, their gene products and the role or function that they play in the physiology, growth, adaptation and ecology of an organism.

There have been major advances in the past decade including the complete sequencing of the *Arabidopsis* genome. This, along with recent rapid progress in sequencing the genome of major agricultural crops, will have a profound effect in all areas of agricultural science, including crop physiology, plant pathology and plant breeding (Hall *et al*., 2000; Weller *et al*., 2001). While it is improbable that weeds will be the primary focus of genomics research there is a high degree of homology among plants, and much of what is learned from studying crop plants will be directly applicable to weeds.

Weed scientists already have used molecular techniques to incorporate herbicide resistance traits into crop plants and, in the course of this research, have contributed immeasurably to knowledge about how genes function in plants, including the role of promoters. They have also exploited molecular approaches to quantify genetic variation among weed populations and to sort out taxonomic relationships among closely related species (Jasieniuk & Maxwell, 2001).

Looking to the future, genomics research will provide weed scientists with crucial knowledge about how weeds survive, grow, interact, adapt, reproduce, evolve and respond to interventions of various kinds, including the application of herbicides or attack by micro-organisms. Marshall (2001) cites, for example, how an understanding of the relationship between genes involved in germination periodicity, reproductive behaviour or competitiveness could have a major impact on our understanding of weed behaviour and how these traits might then be manipulated advantageously.

Genomics research might also lead to the identification of new target sites for herbicides and greatly facilitate rational screening of novel, bio-active chemicals with unique modes of action that selectively modulate such traits as seed dormancy or freezing tolerance in weeds. Alternatively, genomics research undoubtedly will lead to the selection and development of highly competitive crop plants – including ones that can suppress weeds by producing allelochemicals. Current concepts range from increasing the growth rate of seedling crops during the critical period of early establishment by manipulating genes that control plant hormones, to incorporating genes that confer superior stress tolerance to crops, to enhancing the beneficial relationships between crop plants and root colonizing bacteria, endophytes or mycorrhizae (Duke *et al*., 2002).

While the concept of allelopathy has held enduring appeal for weed scientists, its successful exploitation as a practical means of controlling weeds in commercial agriculture has been disappointingly elusive. The science of functional genomics may well change this though, and there is already some promising research underway to increase the production of the allelochemical, sorgoleone, by the roots of sorghum by enhancing expression of the genes encoding for the enzymes involved in its synthesis (Duke, 2003). Such an approach has both its upsides and its downsides, as mentioned by Duke (2003), but in both cases there is a wide spectrum of research opportunities for molecular biologists, physiologists, geneticists and ecologists - and for weed scientists.

Journal rankings: recognition and credibility

So, as weed scientists, what is it that we want to be? Where is it that we must go? Where will the road take us? How will we express ourselves? And who will pay attention?

As a science, our discipline has some distance to go in gaining recognition. It is important that weed science is seen as a credible science and that weed scientists draw from leading experts in other disciplines. It is equally important that weed scientists respond in kind by generating new knowledge that is applicable outside the discipline.

Those who work on ecological approaches to weed management must also be seen to be ecologists. Those who work on weed genomics must be seen as molecular biologists. And those who work alongside farmers - and who in the future will be more concerned about the crop's influence on the weed than the weed's influence on the crop - must be seen as agronomists.

In part, the stature of the discipline will be gauged by the quality of the science reported in weed science journals. The pages of these journals should include fewer articles of the "what happens if" type and more of those that explain "why does this happen". Weed Science needs more articles that add significant new knowledge, fewer articles that repeat hackneyed research protocols, more articles that draw on knowledge bases from outside the discipline (as reflected in journal citations), and fewer of those that include lengthy self-citations or quote only from colleagues and associates.

A comparison of the impact factors of journals as computed by ISI Web of Knowledge provides insight into our current status. Among 55 agronomy journals published world-wide, in 2002 Weed Research and Weed Science were respectably ranked at 8th and 12th positions, respectively (Table 1), based on impact factors which are a measure of the frequency that articles from a particular journal are cited in the literature. The journal impact factor is a measure of the frequency with which the average article in a journal has been cited in a particular year. The impact factor helps evaluate a journal's relative importance, especially when compared to others in the same field. The impact factor is calculated by dividing the number of citations in the current year to articles published in the two previous years by the total number of articles published in the two previous years. It is generally considered that impact factors are a measure of the quality of the journal, with higher impact factors associated with higher quality journals.

Table 1. Agronomy journals rankings by impact factor (IF)*.

Title	IF		Title	IF
1 THEOR APPL GENET	2.26		7 FIELD CROPS RES	1.30
2 ADV AGRON	2.11		8 WEED RES	1.29
3 AGR FOREST METEOROL	2.04		9 PLANT SOIL	1.29
4 MOL BREEDING	2.01		10 PEST MANAG SCI	1.18
5 EUR J PLANT PATH	1.48		11 PLANT PATH	1.16
6 POSTHARVEST BIOL TEC	1.34		12 WEED SCI	0.99
18 WEED TECH	0.76			
38 CAN J PLANT SCI	0.38		…55	

* Summarized from ISI Web of Knowledge 2002 Journal Citation Reports (JCR Science Edition) available online to subscribers at http://isi10.isiknowledge.com/

However, among 135 plant science journals, the highest ranking agronomy journal ranks in 18th spot with Weed Research and Weed Science ranking in 47th and 59th spots, respectively (Table 2).

Table 2. Plant science journals rankings by impact factor (IF)*.

Title	IF		Title	IF
1 ANN REV PLANT BIOL	13.68		7 PLANT MOL BIOL	4.52
2 TRENDS PLANT SCI	12.41		8 ANN REV PHYTOPATH	3.97
3 PLANT CELL	10.75		9 MOL PLANT MICROBE IN	3.84
4 CURR OPIN PLANT BIOL	9.50		10 CRIT REV PLANT SCI	3.70
5 PLANT J	5.85		11 PLANT CELL PHYSIOL	3.08
6 PLANT PHYSIOL	5.80		12 PLANT CELL ENVIRON	3.01
18 THEOR APPL GENET	2.26			
47 WEED RES	1.29			
59 WEED SCI	0.99		…135	

* Summarized from ISI Web of Knowledge 2002 Journal Citation Reports (JCR Science Edition) available online to subscribers at http://isi10.isiknowledge.com/

Additional data on journal citations indicates that the vast majority (2423 of 3923, or approximately 60%) of articles cited in Weed Science and Weed Technology over a period of more than ten years ending in 2002 were articles originally published in Weed Science. Conversely, articles from other leading journals with high impact factors were cited only sparingly. For example articles from the top-ranked agronomy journal, Theoretical and Applied Genetics, with an impact factor of 2.26, were cited only 72 times in Weed Science in a period of more than ten years, whereas articles from Ecology, a highly ranked ecology journal with an impact factor of 3.918, were cited only 51 times, and just five times since 1998.

Perhaps even more telling is the fact that articles from Weed Science were hardly ever cited in articles published in other leading plant science or ecology journals. This could be taken as evidence that weed science as a discipline is not seen to contribute substantially to the enhancement of new or fundamental knowledge in these areas or that it is a peripheral to the mainstream of scientific study. Whatever the case, in today's fast-paced and highly competitive world of science, impact factors, citation indices and other such comparators are being used in assessing the merits of published articles and journals. As such, it will be increasingly important to ensure that the standards applied both in the science, and in the acceptance of papers for publication in weed science journals, are as stringent and demanding as in other areas of agronomy, plant biology and ecology. This in itself will go a long way in enhancing the stature of weed science as an important discipline in both the plant and agricultural sciences.

Acknowledgements

The author acknowledges with appreciation the insights provided by George Marshall and Stephen Duke during the early stages of preparation of this presentation.

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