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Future Research Directions for Weed Science[1]

J. CHRISTOPHER HALL, LAURA L. VAN EERD, STEPHEN D. MILLER, MICHEAL D. K. OWEN, TIMOTHY S. PRATHER, DALE L. SHANER, MEGH SINGH, KEVIN C. VAUGHN, and STEPHEN C. WELLER[2,3]

Abstract: A Research Committee was established by the Weed Science Society of America to outline the direction of weed science research during the next decade. Weeds adversely affect humans in both agricultural and nonagricultural environments. It is the opinion of the research committee that weed science will be advantageously positioned for the future if research focuses on research decision processes, weed biology and ecology, weed control and management practices, herbicide resistance, issues related to transgenic plants, environmental issues, and potential benefits of weeds. These future weed science research directions endorse those of the commodity and grower input group Coalition for Research on Plant Systems (CROPS)'99, a U.S. Department of Agriculture (USDA)-supported initiative. The future of weed science is dependent on a joint effort from industry, government regulators, and the public sector consisting of grower groups, as well as USDA, Agriculture and Agri-Food Canada (AAFC), and university researchers. It is our opinion that efforts spent on these research areas will benefit not only growers, commodity groups, homeowners, and industry, but society at large, through the maintenance and improvement of the food and fiber production system, and the environment in North America.

Abbreviations: AAFC, Agriculture and Agri-Food Canada; CROPS'99, Coalition for Research on Plant Systems (1999); EWRS, European Weed Research Society; GPS, global positioning systems; HRC, herbicide-resistant crops; IWM, integrated weed management; KBDSS, knowledge-based decision support strategies; USDA, U.S. Department of Agriculture; WSSA, Weed Science Society of America.

INTRODUCTION

Based solely on the definition of weeds as plants that are undesirable to human activity at a particular time and place, weeds will always be associated with human endeavors. As we manipulate the environment to suit our needs, we provide an environment suitable for certain weed species. Weeds affect agricultural production, forestry, human health, and noncrop land such as lawns, parks, conservation areas, rights-of-way, aquatic areas, and rangeland. For example, in the early 1990s, the estimated total economic effect of weeds in the United States and Canada was $15.2 billion (Bridges 1994) and $984 million (Swanton et al. 1993), respectively. However, there are measures one can take to minimize the negative effects weeds have on agriculture and other human endeavors.

In Canada and the United States over the last 50 yr, weed scientists have shifted emphasis from herbicide science during a time when food security was a major concern to the general public, to a discipline that focuses on environmentally and ecologically sound agricultural practices. Consequently, weed science research on weed biology and ecology and alternative weed management strategies has increased. In the WSSA Research Committee's opinion, weed scientists must focus on efficient weed control technologies. This will be accomplished by providing the basic and applied knowledge required to develop strategies that provide consistent control and

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[2] Professor, Department of Environmental Biology, University of Guelph, Guelph, ON, Canada N1G 2W1; Ph.D. student, Department of Environmental Biology, University of Guelph, Guelph, ON, Canada N1G 2W1; Professor, Plant Science Division, University of Wyoming, Laramie, WY 82071; Professor, Department of Agronomy, Iowa State University, Ames, IA 50011; Integrated Pest Management Weed Ecologist, University of California, Parlier, CA 93648; Scientist, Agriculture Research Division, American Cyanamid Company, Princeton, NJ 08540; Professor, IFAS, University of Florida, Lake Alfred, FL 33850; Scientist, Southern Weed Science Lab, United States Department of Agriculture, Stoneville, MS 38776; Professor, Horticulture and Landscape Architecture Department, Purdue University, West Lafayette, IN 47907. Corresponding author's E-mail: jchall@evbhort.uoguelph.ca.

[3] The authors are or were members of the WSSA Research Committee.

that are environmentally sensitive and cost effective. Development of new weed control strategies will occur through understanding weed biology and ecology. Various strategies are required for agriculture to remain profitable and meet societal demands for high-quality farm products at a reasonable price while preserving the natural environment. Strategies must move away from single approaches to those that develop multiple and integrated approaches to weed control and crop protection. The influence and necessity of weed science research in noncrop land are also immense, and research in these directions should continue to be supported.

The Research Committee of WSSA has established an inventory of research needs for weed science to direct future research toward a multidimensional approach while considering the demands and needs of society. This paper is not a complete list of research needs. Rather, it is meant to provide a basis to direct both public and private research to expand our current knowledge and understanding of weed science as well as provide a basis for directing future funding. Furthermore, the WSSA Research Committee's suggestions support many of the research needs developed independently by the European Weed Research Society (EWRS) and the U.S. Department of Agriculture (USDA)-supported initiative known as Coalition for Research on Plant Systems (CROPS)'99.

RESEARCH DIRECTIONS

Knowledge-Based and Systems Approach-Based Decision Processes. *Knowledge-based decision support strategies.* Knowledge-based decision support strategies (KBDSS) have been proposed for grazing land management (Lowes and Bellamy 1994), land-use planning (Zhu et al. 1996), greenhouse heat management (Price et al. 1992), and weed management (Johnson and Huggins 1999). To the best of our knowledge, Johnson and Huggins (1999) provide the first detailed description of KBDSS approaches for weed management. KBDSS provide a conceptual framework that integrates data, information, knowledge, and wisdom in the decision-making process. Using experimental knowledge-based concepts in the design of weed management strategies will also allow for the integration of social, economic, and environmental components, thereby improving the utility of these strategies. Johnson and Huggins (1999) state that KBDSS is a first step in integrating weed biology, shaping grower/advisor relationships, and recognizing the importance of long-term studies and experience-building in managing weed populations.

Systems approach-based decisions. A systems approach to solving large- and small-scale problems facing agriculture requires solicitation of in-depth input from growers, agricultural consultants, and rural sociologists if we are to find workable solutions that are easily and rapidly adopted by the agricultural community. A soft-system approach helps develop a research program that poses relevant questions and identifies potential practical solutions. Growers and their consultants are integrators of new techniques developed by weed scientists. Through consultation with interested parties (both agricultural and nonagricultural stakeholders), a sense of ownership develops, thereby assisting in subsequent adoption of workable solutions and new techniques. National programs in Canada and the United States., as well as the priorities of WSSA and CROPS'99, all identify issues that deal with system approaches.

System-based approaches are inherently complex and involve processes for human interaction in addition to the physiological, biological, and ecological processes of weed science. It is important to choose one of the many existing techniques, such as telephone and mail surveys (Wilson and Morren 1990), that best fits the participants in the inquiry process (Michalski 1997). Obtaining input from larger numbers of individuals requires mail or telephone surveys. However, techniques may also be developed by using internet-based sampling methods. Dillman (1978) provides an excellent discussion of the survey process for agricultural disciplines. A measurement of accomplishment in a soft-systems approach is keeping participants involved in the process. A successful systems approach may result in participants agreeing to implement a strategy and, ultimately, wide-scale adoption of the strategy. One successful example of participatory research is the Sustainable Agriculture Farming Systems project, which has been conducted in consultation with growers and private consultants (Clark et al. 1999). The WSSA Research Committee recommends that weed scientists implement the following when conducting research.

1. Include growers, extensionists, agricultural consultants, and a wide cross section of organizations along with weed scientists in the decision process to ensure the development of successful weed science research strategies.
2. Carefully choose appropriate soft-systems techniques in order to construct systems methods that function efficiently and produce results.

Application of the concepts described in this section on decision processes are the first steps toward implementing many of the future research directions outlined in this paper. Whether the decision is to implement new technology or applications, weed science research should embrace the concepts of KBDSS and systems approaches into the decision-making process.

Weed Biology and Ecology. Current information about weed biology and ecology is largely descriptive. Limited information is available about mechanisms of weed interactions with crops and responses of weeds to various production systems. Weeds are perceived by growers to be the most serious impediment to the adoption of conservation tillage practices (Owen 1998). Furthermore, new technological developments promote the use of reduced herbicide doses, variation of herbicide doses within a field, and herbicide-resistant crops (HRC). Use of these new technologies requires growers to make major assumptions about weeds that are not always based on scientific knowledge. Therefore, growers must assume more risk when using new technologies that the public perceives to be beneficial to the environment. For growers to completely benefit from these technologies, mechanistic research must be conducted in weed ecology, genetics, and physiology to increase understanding of the basic processes that regulate weed–crop interactions, weed population dynamics under various management practices, and other aspects of weed invasion, adaptation, and persistence.

Effective weed management strategies cannot be developed until the fundamental relationships of weeds and crops in agricultural systems are fully understood. Weed problems continue to arise, and in many cases, weeds will continue to become more difficult to control in spite of implementation of new technologies. A poor understanding of weed biology and ecology may lead to ineffective use of herbicides and cultivation practices. In addition, research on weed biology and ecology must consider social and economic aspects of weed control, such as practices that select for herbicide-resistant weed populations, declining agricultural profitability, and the belief by society that herbicide use poses a risk to the environment and human health. Most importantly, in order to interpret the results of weed biology and ecology studies, the precise nature of the problem being addressed must be fully understood (Mortensen et al. 2000).

Weed response to selection pressure. The introduction of new cropping practices (e.g., reduced or no-tillage and HRC) may result in shifts in weed species or populations within a species to individuals more able to survive the new practice. New cropping systems have already caused shifts in weed species, resulting in new weed populations that are often more difficult to control. For example, common waterhemp (*Amaranthus rudis* Sauer) has become a major weed problem in the U.S. corn belt because of cropping systems that use specific herbicide groups for weed management. Plant characteristics such as density and reproductive strategy also affect weed population dynamics and response to selection pressure. The relationships between weeds and new cropping practices or technologies need to be understood before unproven weed management programs are implemented. With regard to weed response to selection pressure, the WSSA Research Committee recommends that research be conducted in the following areas.

1. Investigate the ecological relationships between weeds and cropping systems to understand and predict shifts in weed species in response to selection pressure. Such research might be conducted by establishing large, long-term experimental sites and comparing existing and new, innovative crop production systems.
2. Investigate short- and long-term changes in species composition of weed communities, including seedbanks, in the context of succession theory.
3. Investigate dynamics of weed populations that shift in response to selection by control practices, including herbicides, which can cause rapid weed evolution. Such research should be conducted in the context of population and metapopulation theories in order to develop descriptive and predictive models of population behavior.

Traditionally there has been little support for this type of research, as indicated by the disconnection between ecological and weed science literature. Additionally, there has been no organized or concerted effort to establish integrated, large-scale research programs or long-term research sites in weed science. Weed scientists need to demonstrate the relevance of this research in relation to societal goals.

Weed competition and economic thresholds. Weed management practices need to consider economics, time requirements, and potential environmental effects. However, the most important consideration for achieving the most effective weed control is controlling weeds when weed and crop density and growth stage are optimal. There is considerable contention among growers and weed scientists about the importance of determining critical weed thresholds. This research is very difficult to conduct because, within a typical cropping system, five to 10 weed species may be present that have different competitive abilities, crops respond differently to weeds, and crops, weeds, and their interactions are all influenced by environmental conditions. It is also difficult to determine the critical density of a weed population at which significant economic losses begin to occur. In addition, to understand and predict interactions between weeds and crops, the influence of factors such as weed emergence patterns and spatial heterogeneity on seed bank dynamics should be understood.

Research recommendation as described below will provide validation of the economic implications of employing weed thresholds in weed management. The data may also provide a basis by which growers could make decisions to incorporate weed thresholds into their agronomic practices. Most of the research that has been conducted on competition of weeds and crops has focused on a single weed species in a specific cropping situation. Little research has been conducted on competition among crops and mixed weed communities. Furthermore, much of the historic literature was generated using different production systems as well as different crop varieties than are currently used. Recommendations for future research include the following.

1. Investigate the dynamics of weed seedbanks in response to different management systems. Research could focus on individual species, addressing such questions as genetic variation and phenotypic plasticity in populations of seeds or on mixtures of weeds and addressing aboveground community dynamics as influenced by seedbanks. The relationship of seedbanks to aboveground weed floras can be used to make inferences about weed species shifts and seed dispersal patterns.
2. Elaborate upon the extensive descriptive literature on weed–crop competition by investigating ecological and physiological mechanisms of weed–crop and weed–weed competition and weed adaptation to environmental factors, including studies of single weed and crop species as well as mixtures of weeds.
3. Investigate changes in the competitive abilities of weeds and crops in relation to biotic factors, such as plant density and spacing, and abiotic factors of the environment, including disturbance, in order to develop new models and to parameterize existing models of weed–crop competition.
4. Conduct long-term, field-scale studies to determine the effect of utilizing weed thresholds in management on weed seedbanks and subsequent weed problems.

Invasive alien weeds. Invasive alien (also called exotic or nonnative) weed species are a serious threat to natural areas, forest, rangeland, agricultural land, and many other habitats. The term 'noxious weed' is usually reserved for agricultural weeds that have legal definitions in federal and state or provincial laws. Invasive exotic plants are recognized as causing major losses to agricultural, managed, and natural ecosystems. Moreover, these species impede the use of public and private lands. Invasive species are second only to habitat loss as a threat to biodiversity. It is estimated that more than 40.5 million ha (100 million acres) in the United States and Canada (Office of Technology Assessment 1993) are infested with invasive weeds. The issue of invasive weeds received increased political attention when President Clinton issued Executive Order #13112 in February 1999, which calls for a national initiative on invasive species. Presently, weed scientists, ecologists, land managers, and the public do not have the scientific information or the technology to deal adequately with this problem.

Environmental damage and losses because of nonindigenous species in the United States is approximated at $137 billion annually (Pimentel et al. 2000). Efforts to monitor invasive weed problems and control or manage weed infestations need to be improved. New species continue to be introduced unintentionally and intentionally for use in horticulture, pasture improvement, or erosion control. States such as Florida, Texas, New Mexico, Arizona, Hawaii, and California have increased frequencies of new species introduction because of trade, tourism, and transport. The Research Committee of WSSA recommends the following actions.

1. As in the past, federal and state or provincial governments should continue to patrol ports of entry, prevent sales, and enforce importation controls to keep new, potentially invasive species from being introduced. Recently in the United States, these methods were strengthened by passage of the Plant Protection Act. Methods to efficiently recover and identify taxa moving as contaminants in trade goods must be developed. In addition, improving and harmonizing current laws and regulation at all levels of government is required.
2. Coordinated mitigation and control programs should be developed that emphasize integrated weed management (IWM) approaches (i.e., chemical, biological, cultural, and mechanical methods, including prescribed fire regimes). Herbicide efficacy experiments should be conducted that focus on developing application techniques and timing of treatments to maxi-

mize efficacy on target weeds and minimize the effect on nontarget species. Furthermore, restoration programs should be implemented that encourage the use of beneficial species.
3. Prediction methods should be developed to determine what taxa pose a significant threat based on the criteria of Maillet and Lopez-Garcia (2000). Systems should be developed or improved for early detection and quick action to contain or eradicate new infestations.
4. Basic research should be increased on the biology, ecology, physiology, and epidemiology of invasive alien weeds. Methods of spread, including seed dormancy and germination characteristics of invasive species, should be thoroughly understood. Furthermore, basic biological information is needed on the effects of invasive species on ecosystems, endangered species, and crop production sustainability.
5. Education and public awareness should be increased by expanding media coverage, enhancing academic and industry education programs, and improving detection and reporting systems for new invasive weed populations. The number of trained, experienced scientists and staff to conduct research on invasive weeds and to educate the public should be increased. Information management systems should be enhanced to ensure that information and data are freely available for the safe and effective management of invasive weeds.
6. Methods should be developed to determine economic losses caused by invasive weeds to agricultural land management operations.

Genomics. The study of gene structure and function (i.e., genomics) of plants will profoundly influence basic research in plant biology, physiology, and crop improvement during the next decade (Bouchez and Hofte 1998; Somerville and Somerville 1999). Hieter and Boguski (1997, p. 725) refer to functional genomics as the ''development and application of global (genome-wide or system-wide) experimental approaches to assess gene function by making use of the information and reagents provided by structural genomics.'' Complete genomic sequencing of *Arabidopsis* is soon to be completed, and sequencing of rice (*Oryza sativa* L.) has already begun. Genomics and molecular biology techniques can be used to study differences between weed biotypes and to analyze various traits and characteristics of weeds. (This technology also applies to the following sections in this document: Weed Biology and Ecology, Herbicide Resistance, Issues Related to Transgenic Plants, and Potential Benefits of Plant Species Generally Classified as Weeds: Nutraceuticals.)

Weed Control and Management. *Herbicide efficacy enhancement.* Since their introduction in the late 1940s, herbicides have been crucial to modern agriculture. Benefits of herbicide use include reduced tillage, which results in reduced water and wind erosion, and an increase in both crop yield and quality, thereby improving food security in North America. Herbicides are valuable tools in sustainable agriculture where there are several herbicide options for major crops. However, a significant problem throughout Canada and the United States is lack of herbicides registered for use in alternative and small-acre crops, thus seriously limiting the ability of growers to grow these crops and to rotate agronomic practices. Recently there has been a decline in herbicide use because of the increased application of low–use rate herbicides, the deregistration of older herbicides, a reduction in the number of new herbicides introduced, reduced efficacy due to resistant weeds, and concern about food safety and the effect of herbicides on the environment. Optimizing herbicide efficacy will allow for effective weed control while decreasing the amount of active ingredient used.

The use of postemergent herbicides has increased with the development of new products. These herbicides have also made it possible to spray according to the type and density of weeds present in a field. In contrast, preemergent herbicides are applied based on the anticipated weed population. Postemergent herbicides act through contact with the weed foliage. Efficacy of postemergent herbicides is influenced by spray volume, spray droplet size, adjuvants, temperature, humidity, ultraviolet light, soil moisture content, weed size, and weed species. The interactions among these various factors make it impossible to delineate precise use rates for all conditions when the product is first marketed. Thus, use rates recommended are for performance under various application methods and environments. Intensive research has determined that reduced rates often are efficacious when applied using proper methods and the correct adjuvant. For example, efficacy was maintained at significantly lower application rates when nicosulfuron was applied with a specific adjuvant (Nalewaja et al. 1991) or imazethapyr at a lowered water spray rate (Nalewaja and Ahrens 1998). Some herbicides are more effective at higher temperatures and others at lower temperatures, but the response appears to be related to specific weeds. Understanding the response of weeds to herbicides in various climatic conditions will allow for optimization of rates for increased efficacy. Research on efficient herbicide usage can lead to rapid reductions in herbicide use rates and thus reductions in crop production cost.

Precision or site-specific agriculture optimizes agricultural inputs by matching field heterogeneity to varying herbicide application rates. Soil characteristics, weeds, insects, and diseases are neither homogeneous nor static in space or time; therefore, traditional application of herbicides over the surface area of a field may result in over or under application. Precision agriculture utilizes such techniques as global positioning systems (GPS), mapping software, yield monitoring equipment, direct-injection sprayers, remote sensing, and video imaging to address spatial and temporal variability of weeds across a field. Precision technologies in current agricultural practices are coming to the forefront in nutrient management. In weed management, precision agriculture technology has the potential to greatly change and benefit agriculture. However, site-specific weed control needs to be fully analyzed to determine if this technology can fulfill expectations for reducing herbicide use and environmental impact. With present knowledge, it is difficult to correlate field characteristics with the weed populations necessary for site-specific weed control. Vital to site-specific weed control is a cost-effective and accurate method to locate weeds in the field. Once the weeds have been located, the critical threshold when the weeds should be sprayed must be determined. Moreover, weed scientists should take a proactive approach to precision agriculture and ascertain what will happen to weed populations if only weed patches are sprayed. Many questions on precision agriculture remain unanswered. Further research is imperative for site-specific weed control to be a viable tool for growers. Research to maximize herbicide efficacy should include the following.

1. Determine the mode or mechanism of action of adjuvants. Adjuvants that alter the physicochemical properties and enhance the biological activity of herbicides should be developed and used.
2. Improve herbicide formulations to reduce poor and inconsistent efficacy. Increase herbicide rain-fastness through proper formulation and/or adjuvants.
3. Determine the factors influencing herbicide absorption and efficacy, including chemical and physical characteristics of the herbicide, formulation, adjuvant, spray water, spray volume, and spray droplet size, and weed characteristics, such as plant cuticle, size, growth, and stage. Characterize environmental conditions (e.g., temperature, relative humidity, soil moisture) that increase efficacy and determine how these environmental conditions influence plant response to herbicides. Determine optimum spray droplet size to maximize spray retention, minimize off-target drift, and provide sufficient spray deposit to optimize efficacy.
4. Evaluate and improve current application technologies to refine the efficacy of herbicides. Research should be conducted on new methods of application, such as the foam brush and Burch wet blade system (Skroch et al. 1998) and sensor sprays.
5. Determine the potential of split herbicide applications to improve weed control using less total herbicide.
6. Conduct research on crop safety and residue levels for possible use of existing herbicides on alternative and small-acre crops.
7. Make a full analysis of site-specific weed control to determine if this technology can reduce herbicide use and environmental impact. Correlate field characteristics to weed populations necessary for site-specific weed control. Design and determine a cost-effective and accurate method to locate weeds in the field and the critical threshold when the weeds should be sprayed. Proactive approach to precision agriculture should be taken to ascertain what will happen to weed populations if only weed patches are sprayed.

Alternative weed management methods. Alternative methods often only suppress weeds as opposed to providing effective control. Weed management often requires a combination of many alternative methods because one method will not effectively control weeds. Moreover, for implementation of these alternative weed management strategies by the grower, the alternative must be not only efficacious but economical. The effectiveness and advantages of herbicides compared to the lack of viable broad-spectrum alternative weed control options have reduced research into alternative control tactics and their acceptance by growers. Alternative weed management methods include the use of biological agents, natural products, competitive crop cultivars, cover and companion crops, mulches, solarization, and allelopathy. Alternative weed management methods also include nonclassical approaches, such as adjusting the rate and date of crop seeding, using low-disturbance no-till drills, adjusting fertility practices, and changing rotations to avoid major weed species. Not only does the study of the aforementioned areas offer the potential for developing new weed management options, but it also provides insights into weed–crop and weed–pest interactions.

Biological approaches. Although biological agents for weed management have great potential for the future, they have several inherent characteristics that place them at a disadvantage compared to the use of synthetic herbicides. Biocontrol agents such as mycoherbicides and phytotoxins are not widely used because of their poor and inconsistent efficacy under field conditions. The main problem with the use of biological control measures has been that most organisms, whether pathogens or insects, tend to affect a limited number of host plants compared to most herbicides, which are generally broad-spectrum. Both classical and inundative biological approaches have usually focused on a single weed species, thus limiting their applicability in many cropping systems. As well, biocontrol of weeds in annual crops is generally much slower than with herbicides. Because biological methods have not been very attractive for commercialization, the agrochemical industry has expressed little interest in this research. The challenge lies in broadening selectivity and improving the efficacy and reliability of current biological methods. Recommendations for future research include:

1. increasing efficacy and ensuring stability;
2. improving formulations to reduce poor and inconsistent efficacy;
3. increasing knowledge of weed biology and ecology and trophic-level interactions among the biocontrol organism, target weeds, and plant competitors; and
4. developing methods to assess the need to release biocontrol organisms for weed management and to assess the effects of these organisms after release.

Natural products. Natural product chemistry has tremendous potential, and there is a need to continue this area of research. Natural does not always mean better or safer. However, effective and safe natural products may offer growers many acceptable alternatives to synthetic chemical herbicides. Natural products may also result in many economic opportunities for chemical companies to produce new effective herbicides. Plant-derived compounds with potential as natural products include cinmethylin, leptospermone, and artemisinin and their derivatives (Duke et al. 2000). Future research should focus on the discovery of new natural products as potential new lead compounds and for their direct use as weed control agents or their indirect use as allelochemicals.

Competitive crop cultivars. The development of competitive crop cultivars for weed management has been a neglected area of research. The major emphasis in crop breeding has been to improve yields and, in some instances, has inadvertently eliminated many competitive traits in crops. Crop competitiveness can be increased by creating mechanisms of interference, tolerance of the crop to weeds, or both (Pester et al. 1999). Improving competitive ability can be accomplished by plant breeding or through the incorporation of plant genes that enhance crop competitiveness. However, this requires identifying and understanding the factors and plant genes that confer enhanced competitiveness. With the many advances in genetics, increased research effort in this area should yield positive results. Ogg and Seefeldt (1999) characterized competitive traits of winter wheat (*Triticum aestivum* L.) varieties against jointed goatgrass (*Aegilops cylindrica* Host). Similar research could be applied to many agronomic and horticultural crops where herbicide use is limited.

Cover and companion crops. Cover and companion crops are used extensively in tree and vine crops and, to a lesser extent, in vegetable crops to improve soil quality, increase water infiltration, and suppress weeds and other pests. Cover and companion crops reduce wind and water erosion and therefore may reduce off-site herbicide movement. Many growers presently use some form of cover or companion crop for soil conservation and early-season weed management. Widespread use of these techniques has generally not occurred because profitable management systems for diverse cropping situations do not exist. However, there is good potential for the design of cover and companion crops that grow well in specific agronomic situations, out-compete specific weeds, or produce allelopathic chemicals to prevent or minimize weed growth by using classical and molecular genetic approaches to cover crop breeding (Foley 1999). Research should focus on:

1. developing cover crops that fit into specific crop management systems, as well as companion crops that grow well with crops, act to reduce weed infestations, and are competitive against specific problem weeds;
2. identifying systems that are grower friendly and easily used by growers; and
3. finding optimal cover or companion crop architecture and placement to avoid off-site movement of herbicides.

Mulches. Organic and inorganic mulches can effectively suppress annual weeds. Mulches such as bark, paper, straw, rocks, and polyethylene plastic are widely used in many horticultural situations. Inorganic mulches suppress weeds both by acting as a physical barrier and by preventing light penetration. Organic mulches suppress weeds by these means, but may also suppress weeds chemically through allelopathy. Research is required to:

1. determine the effect of mulches on crop yield and on other pests;
2. select plant species that produce sufficient biomass for weed management just prior to planting or transplanting the crop; and
3. adapt this technology into a cropping systems approach.

Solarization. Solarization, which uses plastic film for control of soil-borne organisms, should receive additional attention, particularly in light of deregistration of many soil fumigants. Thermal death requirements for many weed species are unknown. Research is required to determine the optimal duration, seasonal timing, and economics of solarization treatments in different areas of North America. However, it is important to realize that after use, polyethylene plastic and plastic film must be disposed of and often are not biodegradable or environmentally safe.

Allelopathy. The use of natural chemicals produced by plants to reduce or alter weed pressure in crops has been researched for many years. The major impediment to further development in this area is a better understanding of biochemical pathways in plants that produce allelochemicals, of the genes involved in the regulation of these pathways, and of the manipulation of allelopathic cover crops to enhance weed suppression. Allelochemicals may be used as potential models for new pesticidal compounds, including herbicides, fungicides, insecticides, and nematicides. Potential future research in the area of allelopathy include the following.

1. Traditional breeding methods or genetic methods that may be useful in enhancing or introducing allelochemical expression in crop plants.
2. Determination of the potential of crop plants to produce volatile biofumigants that have herbicidal activity.
3. Determination of the release of allelochemicals by a living crop, thereby enhancing competitiveness of the crop.
4. Integration and development of allelopathic cover and companion crops (see Weed Control and Management: Alternative weed management methods: Cover and companion crops) for weed suppression, including research on living mulches (see Weed Control and Management: Alternative weed management methods: Mulches).
5. Combination of solarization (see Weed Control and Management: Alternative weed management methods: Solarization) with the incorporation of phytotoxic plant biomass.

Weed management systems. Development of simulation models that improve weed management strategies and economic returns has not been entirely successful. This lack of success can be attributed to an insufficient database on weed biology and ecology. Currently, there are efforts to develop a regional model that predicts the economic outcome of various management decisions for soybean [*Glycine max* (L.) Merr.] and corn production systems. Another regional model is being developed to describe soil–weed seedbank dynamics. However, there currently is an insufficient database on weed biology and ecology to accommodate decisions about future weed populations and fully field test these regional models. All too often, models are developed that only describe a single weed or a complex of weeds in one crop. Farming is conducted in a much more complex manner than these current models can describe. However, the models PALWEED WHEAT I and II (Kwon et al. 1995, 1998) address many of these issues, including factors such as tillage and crop rotations. Researchers should consider:

1. developing a larger database of weed ecology and biology characteristics;
2. improving and refining weed management system simulation models; and
3. determining the utility of these models as a weed management tool for growers and extensionists, as well as for predicting further areas where research is required.

Herbicide Resistance. The World Health Organization rated pesticide resistance as the third greatest problem in global agriculture, behind soil erosion and pollution (G. Murphy, personal communication). Of the 233 resistant weed biotypes found worldwide, 79 are found within the United States, twice as many as in any other country (Heap 2000). Beckie et al. (1999) estimated the current cost of managing herbicide-resistant wild oat (*Avena fatua* L.) using alternative herbicides in western Canada at over $4 million annually. However in general, it is difficult to estimate the costs associated with yield losses from herbicide-resistant weeds. Considering the influence of weed resistance, which has already been realized in countries such as Australia, it is imperative that research continues on weed resistance and its management. Research required to develop techniques and policies to reduce and manage the evolution of herbicide resistance include:

1. continuing to characterize the mechanism of herbicide resistance using modern techniques of plant physiology and cell and molecular biology;
2. determining the initial frequency of resistant plants within a population, in addition to increased monitoring of the occurrence of herbicide-resistant weed biotypes, and investigating weed population genetics to answer questions about the rate of mutation for resistance and whether resistance is arising from single or multiple plants within a population;
3. investigating herbicide cross- and multiple resistance and fitness of resistant populations to assess alternate control methods and the potential for spread of resistance;
4. validating and extending existing resistance models to evaluate and improve their accuracy for prediction of resistance evolution and spread of herbicide-resistant weeds (e.g., via contaminated seeds, machinery, hay) and determining how to best address these issues;
5. assessing the economic impact of herbicide-resistant weeds using studies at the regional and individual grower level to indicate the economic importance of herbicide resistance;
6. developing IWM strategies to ameliorate the adverse effects of resistant weeds in cropping systems; and
7. determining the role of government in the monitoring and regulation of herbicide-resistant weeds.

Issues Related to Transgenic Plants. Genetics and molecular biology research related to transgenic plants, which began in the late 1970s, has led to the recent development and marketing of transgenic crop varieties. North American growers have rapidly adopted this new technology. It was estimated that 50% of soybean and canola [*Brassica rapa* (L.) Em. Metzg.] crops planted during 1999 in the United States and Canada, respectively, were transgenic. Growers believe transgenic HRCs will make weed management easier, more effective, and/or less expensive than other cultural, chemical, and biological weed management options that are currently available (C. Mallory-Smith, personal communication). However, Europeans have raised issues about the safety of foodstuffs derived from these new transgenic crops, as well as the effect these crops will have on the environment (Masood 1999). There is also concern about the consequences of introgression of herbicide resistance genes to wild relative plants (Masood 1999). Therefore, it is recommended that research focus on the follow points.

1. Analyze the effects and potential consequences of widespread use of transgenic crops, particularly HRCs, on weed population dynamics and weed ecology and of increased weed resistance on weed management and weed control practices. Quantify the selection pressure created by repeated use of herbicides with a specific mode of action and the effect of HRCs on the management of herbicide-resistant weeds.
2. Determine the potential for transgene introgression. This research should focus on introgression of transgenes into wild species closely related to crops and introgression into nontransgenic crops of the same species. Investigation and development of models on the flow of resistance genes from transgenic crops to weeds should aid in the development of guidelines for the use of this technology.
3. Participate in determining the social and economic effects of transgenic crops. This work should be done in collaboration with economists and sociologists to determine the effects of transgenic crops on society. Certainly, all stakeholders in agriculture have a vested responsibility to determine the social and economical effects of transgenic crops.

Environmental Issues. *Herbicide safety.* Herbicides are valuable tools in sustainable agriculture. The fundamental critique of herbicides is that they threaten the safety of humans and the environment. These safety issues are the underlying reason why research is conducted to reduce herbicide rates, improve efficacy, reduce drift, and so on. A largely disregarded aspect of the safety issue is improved handling methods. Although historically, this has not been addressed by the weed science community, pesticide spills during handling are likely to be the single largest source of environmental contamination. Why focus on spray drift if it only accounts for a minor portion of the contribution of pesticides in waterways and ignore point source contamination that may be the major contributing factor? Both of these issues fall under application technology.

Negative aspects of herbicide use include environmental and operator contamination due to improper mixing, loading, and disposal; application of higher than necessary doses; and off-target movement (drift, leaching, and runoff from the treated site). Efforts to improve handling methods through the reduction of treated areas (e.g., through site-specific treatments), spray drift (e.g., through low-drift application methods), and herbicide doses (e.g., through more efficient spray targeting, uptake, and translocation) will help reduce the hazards associated with herbicide use. Key components in achieving these goals include herbicide delivery and formulation systems. Research required to improve herbicide safety includes:

1. development of safer handling systems that allow integrated, closed transfer of herbicides and easy container rinsing, thereby improving operator and environmental safety;
2. implementation of sensing and application technologies that facilitate site-specific treatment, thereby reducing unnecessary application;
3. adoption of low-drift application methods that protect adjacent ecosystems; and
4. utilization of environmental simulation models developed to describe herbicide fate and behavior in the environment, as well as to track and improve efficacy by decreasing losses due to environmental dissipation.

Effects of weeds and weed management on the environment. Weeds can affect soil, water, and air quality beneficially and adversely. Similarly, weed management practices, including herbicide use, cultivation, and many other agronomic techniques, affect the environment. Research should focus on:

1. monitoring changes in the population dynamics of plants, animals, and microbes, in addition to changes in biodiversity as a result of weeds and weed management practices;
2. determining the influence of weeds and weed management on noncrop areas and other pest populations; and
3. investigating changes in habitat due to inundation by invasive weeds and determining how these weeds affect the population dynamics of various species, including those that are threatened or endangered.

Potential Benefits of Plant Species Generally Classified as Weeds. *Nutraceuticals.* Nutraceuticals are products intended to supplement the diet by delivering a concentrated form of a presumed bioactive agent normally found in food. They are presented in a nonfood matrix (e.g., pills, powders) and are used to enhance health in dosages that exceed those obtained from normal foods (Zeisel 1999). Other terms, such as phytochemicals, dietary supplements, medical food, biochemopreventatives, designer food, pharmafood, and functional food (a food with a physiological function), are used in many cases as synonyms. Medicinal foods used for health and medical benefits have been a part of the Chinese culture since 100 BC (Chen and Weng 1998). However in North America and Europe, general public interest in nutraceuticals has increased only during the past 10 to 15 yr. The health benefits of soybean (genistein, isoflavones), tomatoes (*Lycopersicon esculentum* Mill., lycopene), garlic (*Allium sativum* L., allicin), and cruciferous vegetables (glucosinolates), to name a few, have been well publicized. For the year 2000, an estimate of the market value of dietary supplements is $14 billion (Zeisel 1999). Nutraceuticals may be used to mitigate disease, improve health, and lower health care costs, as well as add value to traditional plant species. However, more scientific research is needed to validate claims.

Large potential exists to use weeds or noncrop plants as a source of nutraceutical products. For example, one of the earliest Chinese medicinal plants, kudzu [*Pueraria lobata* (Willd.) Ohwi], contains potent antidipsotropic isoflavones (Keung and Vallee 1998) and has been considered a universal remedy (Mitich 2000). Several weeds are considered botanical supplements, such as buckwheat (*Fagopyrum esculentum* Moench) (Edwardson and Janick 1996) and St. Johnswort (*Hypericum perforatum* L.). Potential research directions include:

1. screening weed species closely related to cultivated vegetables, such as tomato, cruciferous vegetables, and garlic, for their nutraceutical properties and
2. determining the potential of certain weeds species for nutraceutical production, processing, and marketing.

Phytoremediation. Decontamination of soils containing heavy metals remains one of the most intractable problems for remediation. Current remediation techniques are based on either immobilization, extraction by physicochemical techniques, or removal and burial. These techniques require expensive equipment, destroy biological activity in soil, or deleteriously affect soil physical properties (McGrath et al. 1994).

A form of remediation that involves the use of green plants (often weeds) to render harmless, remove, or contain heavy metal contaminants from soil or water has shown promising potential. This approach termed ‘‘phytoremediation’’ exploits plant-based physical, chemical, and biological processes to remediate contaminated soils (Cunningham et al. 1995). There are two types of phytoremediation: phytostabilization and phytoextraction. Phytostabilization involves using plants to stabilize contaminated soil, thereby decreasing wind and water erosion, water infiltration, and contaminant leaching. Phytoextraction involves heavy metal removal from soil or water by extraction and containment in aboveground portions of the plant (Cunningham et al. 1995). Similar techniques could possibly be used to remediate soil with organic contaminants such as polychlorinated biphenyls. Research areas include:

1. screening weed species for their ability to accumulate or tolerate heavy metals at high concentrations;
2. evaluating weed characteristics that favor tolerance or accumulation of heavy metals, such as rooting pattern and depth, water extraction and use, ion absorption, transport and entrapment, internal tolerance mechanisms, biotransformation, and rhizosphere associations with plants;
3. improving the ability of a plant to tolerate or accumulate heavy metals through conventional breeding and molecular techniques; and
4. carrying out cost–benefit analyses of phytoremediation techniques.

CONCLUSIONS

This document, prepared by the Research Committee of WSSA, is designed to direct future weed science research. Similarly, Kropff and Walter (2000) suggested that future research directions for EWRS with regard to weed management should include prevention (prediction of weed effects through adapted crop management), control (improvement of technology with respect to herbicide application and efficacy), and decision making (improved information technology with respect to weed management). The suggestions for future research stated in this manuscript support those of CROPS'99. Research priorities developed from the CROPS'99 initiative that are applicable to weed science are listed below.

1. Expand the science and application of plant genomics, thereby providing the basic knowledge and technology required to increase the productivity and utility of plants.
2. Develop efficient, sustainable systems for the production of food and fiber and preservation of the natural resource base.
3. Develop mechanisms to enhance producer profitability while minimizing financial risks and ensuring food safety and security.

Moreover, Glasener (personal communication) outlined WSSA's eight priority areas for research, which overlap with those of the CROPS'99 initiative and our recommendations.

1. Research invasive weeds.
2. Develop a systems approach to understanding the effects and management of weeds.
3. Increase the understanding of biology related to growth, development, and competition of weeds.
4. Minimize the effects of herbicide use on surface waters and groundwater.
5. Control weeds using biological agents and natural products.
6. Modify application technology to increase the efficiency of weed management.
7. Understand and manage the occurrence of weed resistance to herbicides.
8. Increase the efficiency and accuracy of detecting herbicides in the environment.

Attaining the research objectives outlined by the WSSA Research Committee will involve a joint effort by industry, regulators, and the public sector, consisting of Agriculture and Agri-Food Canada (AAFC), the USDA, and university researchers. Moreover, we must ensure that weed science meets the needs of society, farmers, commodity and conservation groups, and environmental organizations. Concerned citizens should be encouraged to offer their ideas and suggestions as to the direction of weed science. With food security less of an issue in North America, agricultural science and technology are now focusing more on the social and environmental effects of weeds and weed management practices. The future of weed science relies on a multidimensional approach for weed control. Such a system will work toward a socially permissible, environmentally sound, economically feasible, productive and sustainable agricultural system. The research objectives discussed in this paper will benefit not only the growers, but scientists, consumers, and all of society.

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LITERATURE CITED

Beckie, H. J., A. G. Thomas, A. Légère, D. J. Kelner, R. C. Van Acker, and S. Meers. 1999. Nature, occurrence, and cost of herbicide-resistant wild oat (*Avena fatua*) in small-grain production areas. Weed Technol. 13: 612–625.

Bridges, D. C. 1994. Impact of weeds on human endeavors. Weed Technol. 8:392–395.

Bouchez, D. and H. Hofte. 1998. Update on genomics: functional genomics in plants. Plant Physiol. 118:725–732.

Chen, J. and W. Weng. 1998. Medicinal food: the Chinese perspective. J. Med. Food 1:117–122.

Clark, S., K. Klonsky, P. Livingston, and S. Temple. 1999. Crop yield and economic comparisons of organic, low-input, and conventional farming systems in California's Sacramento Valley. Am. J. Altern. Agric. 14:109–121.

Cunningham, S. D., W. R. Berti, and J. W. Huang. 1995. Remediation of contaminated soils and sludge by green plants. *In* R. E. Hinchee, J. L. Means, and D. R. Burns, eds. Bioremediation of Inorganics. Columbus, OH: Batelle Press. pp. 33–54.

Dillman, D. A. 1978. Mail and Telephone Surveys: The Total Design Method. New York: Wiley Interscience. 325 p.

Duke, S. O., F. E. Dayan, J. G. Romagni, and A. M. Rimando. 2000. Natural products as sources of herbicides: current status and future trends. Weed Res. 40:99–111.

Edwardson, S. and J. Janick. 1996. Buckwheat: pseudocereal and nutraceutical. Progress in New Crops: Proc. Third Natl. Symp. 22–25:195–207.

Foley, M. E. 1999. Genetic approach to the development of cover crops for weed management. *In* D. D. Buhler, ed. Expanding the Context of Weed Management. New York: Hayworth Press. pp. 77–95.

Heap, I. 2000. International Survey of Herbicide-Resistant Weeds. Online February 15, 2000. Available at http://www.weedscience.com.

Hieter, P. and M. Boguski. 1997. Functional genomics: it's all how you read it. Science 278:601–602.

Johnson, G. A. and D. R. Huggins. 1999. Knowledge-based decision support strategies: linking spatial and temporal components within site-specific weed management. *In* D. D. Buhler, ed. Expanding the Context of Weed Management. New York: Hayworth Press. pp. 225–238.

Keung, W. M. and B. L. Vallee. 1998. Kudzu root: an ancient Chinese source of modern antidipsotropic agents. Phytochemistry 47:499–506.

Kropff, M. J. and H. Walter. 2000. EWRS and the challenges for weed research at the start of a new millennium. Weed Res. 40:7–10.

Kwon, T. J., D. L. Young, F. L. Young, and C. M. Boerboom. 1995. PALWEED:WHEAT: a bioeconomic decision model for postemergence weed management in winter wheat (*Triticum aestivum*). Weed Sci. 43:595–603.

Kwon, T. J., D. L. Young, F. L. Young, and C. M. Boerboom. 1998. PALWEED:WHEAT II: revision of a weed management decision model in response to field testing. Weed Sci. 46:205–213.

Lowes, D. and J. A. Bellamy. 1994. Object orientation in a spatial decision support system for grazing land management. Artif. Intell. Applic. 8:55–66.

Maillet, J. and C. Lopez-Garcia. 2000. What criteria are relevant for predicting the invasive capacity of a new agricultural weed? The case of invasive American species in France. Weed Res. 40:11–26.

Masood, E. 1999. Britain backs biotech, seeks tougher regulation. Nature 399: 228.

McGrath, S. P., C. M. Sidoli, A.J.M. Baker, and R. D. Reeves. 1994. Using plants to clean-up heavy metals in soil. *In* 15th World Congress of Soil Science. Volume 4a. Acapulco, Mexico, July 10–16. Madison, WI: International Soil Science Society. pp. 310–312.

Michalski, W. J. 1997. Tool Navigator. Portland, OR: Productivity Press. pp. 213–272.

Mitich, L. W. 2000. Kudzu [*Pueraria lobata* (Willd.) Ohwi]. Weed Technol. 14:231–235.

Mortensen, D. A., L. Bastiaans, and M. Sattin. 2000. The role of ecology in the development of weed management systems: and outlook. Weed Res. 40:49–62.

Nalewaja, J. D. and W. H. Ahrens. 1998. Adjuvants and spray volume affect herbicide efficacy. *In* P. McMullan, ed. Proceedings of the Fifth International Symposium on Adjuvants for Agrochemicals. Memphis, TN. pp. 434–441.

Nalewaja, J. D., Z. Woznica, and F. A. Manthey. 1991. DPX-V9360 efficacy with adjuvants and environment. Weed Technol. 5:92–96.

Office of Technology Assessment. 1993. Harmful Non-Indigenous Species in the United States. OTA-F-565. Washington, DC: Government Printing Office.

Ogg, A. G., Jr. and S. S. Seefeldt. 1999. Characterizing traits that enhance the competitiveness of winter wheat (*Triticum aestivum*) against jointed goatgrass (*Aegilops cylindrica*). Weed Sci. 47:74–80.

Owen, M.D.K. 1998. Producer attitudes and weed management. *In* J. L. Hatfield, D. D. Buhler, and B. A. Stewart, eds. Integrated Weed and Soil Management. Ann Arbor, MI: Ann Arbor Press. pp. 43–59.

Pester, T. A., O. C. Burnside, and J. H. Orf. 1999. Increasing crop competitiveness to weeds through crop breeding. *In* D. D. Buhler, ed. Expanding the Context of Weed Management. New York: Hayworth Press. pp. 59–76.

Pimetel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and Economic Costs of Nonindigenous Species in the United States. BioScience 50:53–65.

Price, D. R., T. H. Chen, and R. M. Peart. 1992. A knowledge-based system for control of waste heat for a greenhouse–aquaculture complex. Energy World Agric. 5:33–46.

Somerville, C. and S. Somerville. 1999. Plant functional genomics. Science 285:380–382.

Skroch, W. A., A. D. Worsham, S. E. Henson, and R. L. Wahlers. 1998. Efficacy and application with the Burch wet blade system. Proc. South. Weed Sci. Soc. 51:218.

Swanton, C. J., K. N. Harker, and R. L. Anderson. 1993. Crop losses due to weeds in Canada. Weed Technol. 7:537–542.

Wilson, K. K. and G.E.B. Morren Jr. 1990. Systems Approaches for Improvement in Agriculture and Resource Management. New York: Macmillan. 361 p.

Zeisel, S. H. 1999. Regulation of ''Nutraceuticals.'' Science 285:1853–1855.

Zhu, X., R. J. Aspinall, and R. G. Healey. 1996. ILUDSS: a knowledge-based spatial decision support system for strategic land use planning. Comput. Electron. Agric. 15:279–301.