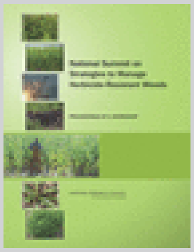


National Summit on Strategies to Manage Herbicide-Resistant Weeds: Proceedings of a Symposium

ISBN
978-0-309-26556-0

66 pages
8 1/2 x 11
PAPERBACK (2012)

Planning Committee for a National Summit on Strategies to Manage Herbicide-Resistant Weeds; Board on Agriculture and Natural Resources; Division on Earth and Life Studies; National Research Council

National Summit on Strategies to Manage Herbicide-Resistant Weeds

PROCEEDINGS OF A WORKSHOP

Organized by the
Planning Committee for a National Summit on
Strategies to Manage Herbicide-Resistant Weeds

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was funded by the Herbicide Resistance Action Committee, the Iowa Soybean Association, the National Cotton Council of America, the United Soybean Board, the U.S. Department of Agriculture, Economic Research Service; the U.S. Department of Agriculture, National Institute of Food and Agriculture; and the Weed Science Society of America. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-26556-0
International Standard Book Number-10: 0-309-26556-8

Cover: Photos credits from top of the page: waterhemp, U.S. Department of Agriculture, Agricultural Research Service; wheat, U.S. Department of Agriculture; johnsongrass, U.S. Department of Agriculture, Agricultural Research Service (Barry Fitzgerald); sugarbeets, U.S. Department of Agriculture; farmer and corn, ©iStockphoto.com/Chris Fertnig; marestail, Ohio State University Extension; alfalfa, U.S. Department of Agriculture, Agricultural Research Service.

Additional copies of this report are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu/.

Printed in the United States of America.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

PLANNING COMMITTEE FOR
A NATIONAL SUMMIT ON STRATEGIES TO MANAGE HERBICIDE-RESISTANT WEEDS

CHARLES J. ARNTZEN (*Chair*), Arizona State University, Tempe
HAROLD D. COBLE, U.S. Department of Agriculture, Agricultural Research Service
DAVID E. ERVIN, Portland State University, Oregon
JODIE S. HOLT, University of California, Riverside
TERRANCE M. HURLEY, University of Minnesota, St. Paul
RAYMOND A. JUSSAUME, JR., Michigan State University, East Lansing
MICHEAL D. K. OWEN, Iowa State University, Ames
JILL SCHROEDER, New Mexico State University, Las Cruces
DAVID R. SHAW, Mississippi State University, Mississippi State

Staff

KARA N. LANEY, Program Officer
RUTHIE S. ARIETI, Research Associate

BOARD ON AGRICULTURE AND NATURAL RESOURCES

Acknowledgments

This proceedings has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published proceedings as sound as possible and to ensure that the proceedings meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following for their review of this proceedings:

Stephen O. Duke, U.S. Department of Agriculture, Agricultural Research Service, University, Mississippi
David E. Ervin, Portland State University, Oregon
Jerry Green, DuPont Ag Biotechnology/Pioneer Hi-Bred International, Newark, Delaware
Raymond A. Jussaume, Jr., Michigan State University, East Lansing
Nancy Ragsdale, U.S. Department of Agriculture, Agricultural Research Service (retired), Beltsville, Maryland
Siyuan Tan, BASF Corporation, Research Triangle Park, North Carolina
Alan Tasker, U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Riverdale, Maryland

Although the reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of this proceedings before its release. The review of this proceedings was carried out in accordance with institutional procedures and all review comments were carefully considered.

The National Research Council would like to thank the generous sponsors of this project.

Herbicide Resistance Action Committee
Iowa Soybean Association
National Cotton Council of America

United Soybean Board
U.S. Department of Agriculture, Economic Research Service
U.S. Department of Agriculture, National Institute of Food and Agriculture
Weed Science Society of America

Preface

Preserving the efficacy of herbicides and of herbicide-resistance technology depends on awareness of the increasing resistance of weeds to herbicides used in agriculture and coordinated action to address the problem by individuals at the farm level and beyond. This summit served as a venue to bring the attention of important stakeholders to the issue and as an opportunity for experts from diverse disciplines to strategize in a coordinated way to address herbicide-resistant weeds. In convening stakeholders for this event, participants took a step toward a recommendation from the 2010 National Research Council report, *The Impact of Genetically Engineered Crops on Farm Sustainability in the United States*, that federal and state government agencies, private-sector technology developers, universities, farmer organizations, and other relevant stakeholders collaborate to document emerging weed-resistance problems and to develop cost-effective resistance-management programs and practices that preserve effective weed control. The summit provided the opportunity for stakeholders to explore the scientific basis of the emergence of herbicide resistance and to consider different perspectives on both opportunities and barriers to overcoming the problem of herbicide-resistant weeds. Summaries, presentation materials, and a video recording of the summit can be found at http://nas-sites.org/hr-weeds-summit/. This document contains a brief synopsis of key points made by each speaker at the summit. The National Research Council does not endorse the statements made by summit presenters.

Horseweed (Marestail. *Conyza canadensis*; mature plant), courtesy of the Weed Science Society of America.

Contents

Welcome

Charles J. Arntzen
Arizona State University

This summit grew out of a 2010 National Research Council report on the impact of genetically engineered crops on U.S. farm sustainability. A variety of topics were addressed in the report, and one of the findings was that weeds resistant to glyphosate were an emerging problem. Since the time the report was published, glyphosate resistance in weeds has more than "emerged"—it is now a significant problem.

Let me provide some background on this topic from my own personal perspective. When my dad was planting corn in the 1940s in western Minnesota, he used the Check Planting Method. You would have a quarter mile of heavy wire, which you would stake at either end of the field. A planter would go over it, and every time the planter hit a little button on this wire, the hopper would open and release a few seeds that would grow and make a hill of corn. It took my dad two days or more to plant a plot of land that today would take an hour and a half with a modern corn planter, but the end result for my dad was a beautiful corn field that looked similar to a checker board—all the rows were in perfect alignment. He followed this system because at the time there were no options for controlling weeds except cultivation. This planting method allowed him to cultivate both North-South and East-West from May through early July to optimally remove all weeds from the field. It was labor and time intensive. Along with my dad, I operated the tractor for many hours in many spring seasons, cultivating.

In the 1950s, the triazine herbicides were developed.[1] Atrazine was particularly significant for corn. On our farm, my father was an early adopter of the new technology. He would spray triazine herbicides at the time of planting, and the herbicide would prevent weeds from emerging. This saved time and cost since manual cultivation was no longer needed. Controlling weeds with herbicides also freed me up from time spent sitting on a tractor, so I could get a summer job in town and earn money for college.

[1]Appendix D includes a table of herbicide classifications and mechanisms of actions for herbicides discussed in the proceedings.

I did not spend much time thinking about herbicides after I left the farm until 20 years later, when I was on the faculty of the University of Illinois, Urbana-Champaign. At the time, I was doing basic scientific research on chloroplast development, photosynthesis, and how electron transfer occurs in chloroplasts. Fred Slife, who was the "dean" of the weed science community in Illinois, asked me if I had heard about triazine-resistant weeds and told me I should take a look at them. Triazines were known to kill plants by blocking photosynthesis. But fields had been discovered which were full of pigweed that survived multiple applications of atrazine. When my fellow researchers and I looked at isolated chloroplasts from the resistant pigweed, we found that they could not bind atrazine and, as a result, the herbicide would not stop the electron transport that supports all photosynthesis. This led to cloning the gene for the triazine-binding protein from the resistant pigweed to show that there was a single base substitution in this one gene, and that this site controlled the binding of atrazine to its receptor. This type of mutation was also seen in lamb's quarters and other weeds.

In the 1980s, I ended up working on this issue at DuPont, studying the genetic changes that could create resistance to the acetolactate synthase (ALS) class of herbicide. The idea was that if exposure to herbicides could trigger weeds' selection-pressure response[2] and thereby change their receptors to herbicides to block binding and herbicide action, the same change could be made in crops using biotechnology approaches. During this time, DuPont and Monsanto both were working on developing crops that combined superior crop-protection chemistry with superior genetics. It was an exciting time in plant biotechnology. Monsanto benefited from its earlier chemical screening program in which a molecule that resembles an amino acid was found to be toxic to virtually all plants. This was called glyphosate. A very attractive feature of this herbicide was that it did not get into the groundwater because it bound to the clays in the soil. Also, bacteria could degrade it in the soil, and it was nonselective. Glyphosate would kill all plants, including crops, unless the latter were made herbicide resistant through genetic engineering. Monsanto introduced Roundup Ready® soybeans, which were resistant to glyphosate, in 1996, followed the next year by cotton and canola, and corn the year after that.

If I could have asked my dad what he thought about the development of glyphosate-resistant crops, he very likely would have said it was a no-brainer. Glyphosate is environmentally friendly, it gives the farmer greater flexibility in the timing of herbicide application, and its use means farmers do not have to mix different chemicals. My dad would have adopted glyphosate-resistant crops. Tens of thousands of farmers made that decision.

The purpose of this summit is to ask "What happens when tens of thousands of farmers use the same form of weed control over millions of acres?" We are not going to deliver any silver-bullet solutions today at this summit, but we hope to emphasize issues of what we do next where herbicide-resistant weeds have emerged, and what we do in the parts of the country where the problem is not yet full blown.

---

[2]Selection pressure is the accumulation of numerous or single factors in an environment which differentiate the fitness of organisms that occupy the environment. In the case of weeds, the herbicide is the primary factor that differentiates for a specific trait, that is, resistance to the herbicide. Weed biotypes with the trait for resistance to a particular herbicide or herbicides will be favored in an environment where the herbicide is used and will become the dominate biotype.

Herbicide Resistance in Weeds: What is the Nature of the Problem?

Micheal D. K. Owen
Iowa State University

Weeds represent the most important pest complex threat to global food security; they cause more loss of productivity and economic cost to humanity when compared to all other pest complexes combined. Furthermore, more agricultural acres are treated with herbicides to address the production issues caused by weeds than the acreage treated with all other pesticide classes combined. However, weeds have not been seen as a serious problem, given the general success of using herbicides to manage widespread weed problems. When genetically engineered herbicide resistance was introduced into many major crops, the concerns for weeds further declined, as weed control was perceived as simple and convenient. The historic perspective would suggest that weed control should not be considered as either simple or convenient given the ability of weeds to evolve resistance to all herbicides, including those for which genetically engineered traits were developed in crops. Currently there are 388 herbicide-resistant weed biotypes represented by 208 weed species.[1] These evolved resistances include resistance to all of the commercially available herbicide mechanisms of action. One or more of these resistances may be represented in a given species. Over the last decade, resistance in (currently) 23 weed species has evolved to glyphosate, and the production of corn, cotton, and soybean is threatened by the increasing numbers of glyphosate-resistant weeds in an increasing number of crop fields. It is important to recognize that the ever-increasingly important problem with herbicide-resistant weeds is not an herbicide problem. Furthermore, evolution of herbicide resistance in weeds is not a genetically engineered crop problem. The evolution of herbicide resistance in weeds represents a behavioral problem with the management and application of herbicides.

The changes in weed populations brought forward by the use of herbicides represent the selection of the fittest as described by Charles Darwin more than 100 years ago. The evolution of herbicide-resistant weed biotypes, however, illustrates Darwinian

[1]Numbers current as of May 2012.

evolution in fast forward. Given the predominance of using herbicides to control weeds, to the exclusion of other more diverse tactics and strategies, the production of crops has become simplified and places an incredible selection pressure on the weed populations that exist within the crop production systems. Essentially, agriculture is very quickly selecting for the pests that are best adapted to the tactics and strategies used to control them.

Specific weeds with evolved resistances to many herbicide mechanisms of action are becoming increasingly important. While there are several extremely important weed species that have evolved resistance to herbicides, common waterhemp (*Amaranthus tuberculatus syn. rudis*) is of particular note, given its widespread presence in the Midwest United States. Common waterhemp exhibits a number of characteristics that make it particularly “weedy”; these characteristics include but are not limited to a dioecious reproductive habit (obligate outcrossing), high seed productivity, opportunistic germination, and the demonstrable ability to evolve resistance to herbicides. Common waterhemp populations have evolved resistance to triazine herbicides, the ALS-inhibitor herbicides, the protoporphyrinogen oxidase (PPO)-inhibitor herbicides, the hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor herbicides, the growth-regulator herbicides, and glyphosate. There are specific populations of common waterhemp that have evolved multiple resistances to as many as five different herbicide mechanisms of action. Given that, to date, most of the evolved herbicide resistances are dominant traits; these evolved traits will spread quickly. The speed is enhanced by a failure of those involved in agriculture to adopt alternative strategies for the management of weeds.

In the opinion of the author, it is clear that, thus far, agriculture is not accepting the importance of herbicide resistance nor willing to react to the need for changes in weed-management tactics and strategies. There continue to be disconnects between the long-term perspectives of herbicide-resistant weeds and the short-term concerns about profitability for agricultural producers as well as within agricultural chemical companies. There are also important questions about whether herbicide resistance can and should be regulated. However, there should be no question about whether herbicide resistance should be managed. Evolved resistance to herbicides in important weed species will continue to be an increasing problem that changes at an increasing rate unless stewardship is implemented in all crop-production systems immediately.

KEY POINTS

- Herbicide resistance is not a new problem.
- Globally, resistance has evolved for ***all*** herbicide mechanisms of action.
- The rate of resistance evolution has accelerated; more farmers rely on single herbicides to control weeds.
- Herbicide resistance is ***not*** an herbicide or genetic-engineering problem but a behavioral problem.

Waterhemp (*Amaranthus tuberculatus syn. rudis*), courtesy of the U.S. Department of Agriculture, Agricultural Research Service.

The Epidemiology of Herbicide Resistance

Jodie Holt
University of California, Riverside

Herbicide resistance is the naturally occurring ability of some plants to survive treatment at a normal field dosage of the herbicide. Resistance is a universal phenomenon among living organisms and has been found in bacteria to antibiotics, fungi to fungicides, insects to insecticides, and plants to herbicides. While resistance to herbicides was discovered later in time than resistance in other pest organisms, the number of cases worldwide is large and continuing to increase. Resistance is a biological phenomenon that results from environmental selection on the genetic diversity of living organisms. Random mutations are common, and resistant genes likely already exist in weed populations. Since genetic traits are inherited from parents, resistant plants will pass the genes for resistance to their offspring. Under selection by the environment, the best adapted plants will leave more offspring; thus, when an herbicide is present in the environment, any plants resistant to that herbicide will be best adapted, survive, and leave more offspring than susceptible plants. After several cycles of selection by the same herbicide, an entire population of weeds can be resistant where formerly there were only susceptible plants. Resistant plants are genetic variants of the same species as susceptible biotypes. This change in traits (genes) of a population of a species over time is evolution, which can occur over very short time frames.

There are many agricultural practices, including nonchemical ones, that have the potential to kill susceptible weeds and that select for weeds best adapted to those practices. The result of this selection can be very rapid evolution (genetic change within populations of a species) or very rapid succession (shifts in entire species to others that are better adapted to the agricultural practices). In addition to evolution of herbicide resistance, many examples of rapid weed succession have been observed in a variety of cropping systems. For example, repeated mowing can select weeds with predominantly prostrate growth forms; perennial cropping systems (e.g., orchards) often select perennial weeds; and weed species typically shift from predominantly grass weeds to broadleaf (dicot) weeds following repeated use of grass-specific herbicides. Any herbicide chemistry or use pattern that increases selection pressure on weeds constitutes a high risk for evolution of resistance. The general principle that should guide all weed management is to reduce the selection pressure caused by repeatedly using the same method of control (chemical or nonchemical). In other words, care should be taken to manage selection pressure on weeds.

KEY POINTS

- *Understand the biology first!*
- Resistance is:
  - Universal among living organisms, from bacteria to antibiotics, insects to insecticides, and plants to herbicides.
  - A biological phenomenon that results from environmental selection on the genetic diversity of living organisms; the best adapted plants leave more offspring.
  - A response to selection—weed control, including use of the same herbicide, is a form of selection.
- Resistance is ***not***:
  - Restricted to herbicides; continuous use of ***any*** practice will select for best-adapted weeds resulting in evolution of resistant biotypes or succession to adapted species.
- Principles from biology that underpin resistance management include:
  - Increased selection pressure causes resistance to evolve.
  - Herbicide-resistant and susceptible biotypes need to be controlled equally.

Palmer amaranth (*Amaranthus palmeri*), courtesy of the Weed Science Society of America.

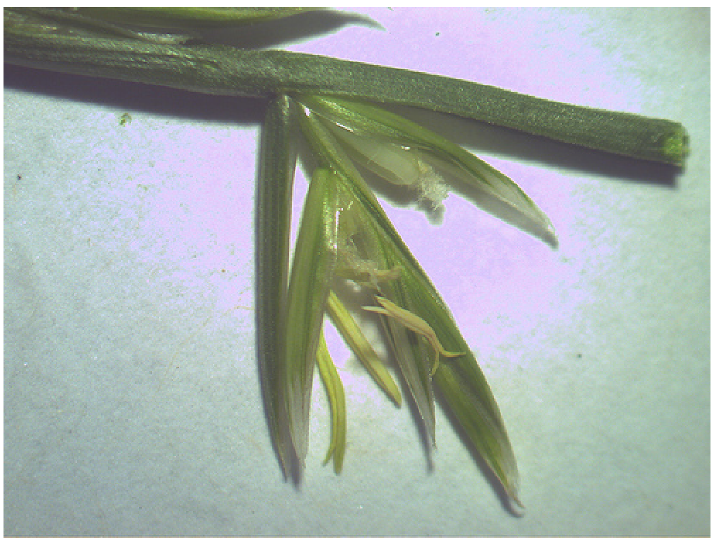
The Australian Experience of Managing Herbicide Resistance and Its Contrasts with the United States

Michael Walsh
University of Western Australia

Since the 1990s, the grain-growing regions of Australia have experienced a major problem with herbicide-resistant weeds. This occurred because of a unique combination of events. First, the highly productive pasture species annual ryegrass (*Lolium rigidum*) was present at high densities across vast areas devoted to livestock production. Then, from the 1970s, much of this pasture land dominated by *Lolium* was converted to wheat fields. With this dramatic shift from livestock to crop production, *Lolium* instantly was a problematic crop weed. The newly available acetyl coenzyme-A carboxylase (ACCase) herbicides were used widely and persistently. Herbicide use without diversity on huge populations of genetically variable *Lolium* across vast areas resulted in widespread resistance evolution. Cross pollination among resistant survivors ensured multiple herbicide resistance and the loss of efficacy of many herbicides. This shattered the illusion of herbicide invincibility and drove the search for integrated control strategies. Multiple resistance forced diversity in weed-control practices and the use of both herbicide and nonherbicide tools for sustainable weed control. For example, *Lolium*, like many crop weeds, relies on annual seed production and seed maturity is synchronized with crop maturity. Importantly, *Lolium* seed remains attached to the plant at the same height as the crop seed heads at grain harvest. Modern grain harvesters are efficient at sorting weed seed from crop grain, thus some 95 percent of *Lolium* seeds pass intact through the grain harvester to be returned to the crop field in the chaff fraction, perpetuating the ongoing weed problem. Therefore, grain harvest represents an excellent opportunity to target *Lolium* seed production. Toward this, Australian farmers have developed and adopted several “harvest weed seed control” (HWSC) systems that effectively target annual ryegrass and other weed seeds during the harvest operation. The HWSC systems currently used in Australia include chaff carts, direct harvest residue baling, narrow windrow burning, and the recently introduced Harrington Seed Destructor. The use of HWSC in addition to herbicidal weed control now has been proven to reduce *Lolium* infestations dramatically, clear evidence of the value of new weed-control tools in prolonging the life of herbicides.

KEY POINTS

- When ryegrass pastures were converted to wheat production in Australia, ryegrass (*Lolium*) became the main weed.
- Australian farmers have developed and adopted several "harvest weed seed control" (HWSC) systems that effectively target annual ryegrass and other weed seeds during the harvest operation. The use of HWSC in addition to herbicidal weed control now has been proven to reduce *Lolium* infestations dramatically.



Annual Ryegrass (*Lolium rigidum*), courtesy of Macleay Grass Man (http://freeimagefinder.com/detail/7370410186.html).

Best Management Practices to Control and Combat Resistance[1]

David R. Shaw
Mississippi State University

Mitigating the evolution of herbicide resistance depends on reducing selection through diversification of weed-control techniques, minimizing the spread of resistance genes and genotypes via pollen or propagule dispersal, and eliminating additions of weed seed to the soil seedbank. Effective deployment of such a multifaceted approach will require shifting from the current concept of basing weed management on single-year economic profitability. Programs for herbicide-resistance management must consider use of all cultural, mechanical, and herbicidal options available for effective weed control in each situation and employ the following best management practices (BMPs):

1. Understand the biology of the weeds present.
2. Use a diversified approach toward weed management focused on preventing weed seed production and reducing the number of weed seeds in the soil seedbank.
3. Plant into weed-free fields and then keep fields as weed free as possible.
4. Plant weed-free crop seed.
5. Scout fields routinely.
6. Use multiple herbicide mechanisms of action (MOAs) that are effective against the most troublesome weeds or those most prone to herbicide resistance.
7. Apply the labeled herbicide rate at recommended weed sizes.
8. Emphasize cultural practices that suppress weeds by using crop competitiveness.
9. Use mechanical and biological management practices where appropriate.
10. Prevent field-to-field and within-field movement of weed seed or vegetative propagules.
11. Manage weed seed at harvest and after harvest to prevent a buildup of the weed seedbank.
12. Prevent an influx of weeds into the field by managing field borders.

[1]This summary is excerpted from the position paper endorsed by the Weed Science Society of America and submitted to the U.S. Department of Agriculture and the U.S. Environmental Protection Agency.

To address the increasingly urgent problem of herbicide resistance, the following recommendations are offered:

1. Reduce the weed seedbank through diversified programs that minimize weed-seed production.
2. Implement an herbicide MOA labeling system for all herbicide products and conduct an awareness campaign.
3. Communicate that discovery of new, effective herbicide MOAs is rare and that the existing herbicide resource is exhaustible.
4. Demonstrate the benefits and costs of proactive, diversified weed-management systems for the mitigation of herbicide-resistant weeds.
5. Foster the development of incentives by government agencies and industry that conserve critical herbicide MOAs as a means to encourage adoption of best practices.
6. Promote the application of full-labeled rates at the appropriate weed and crop growth stage. When tank mixtures are employed to control the range of weeds present in a field, each product should be used at the specified label rate appropriate for the weeds present.
7. Identify and promote individual BMPs that fit specific farming segments with the greatest potential impact.
8. Engage the public and private sectors in the promotion of BMPs, including those concerning appropriate herbicide use.
9. Direct federal, state, and industry funding to research addressing the substantial knowledge gaps in BMPs for herbicide resistance and to support cooperative extension services as vital agents in education for resistance management.

KEY POINTS

- Best management practices (BMPs) must be based on an understanding of the biology of the problem weeds.
- The goal is to reduce selection pressure through diversification of weed-control techniques, minimize the spread of resistance genes and genotypes via pollen or propagule dispersal, and eliminate additions of weed seed to the soil seedbank.
- Effective deployment of such a multifaceted approach will require shifting from the current concept of basing weed management on single-year economic thresholds.
- BMPs must be tailored to the individual situation and consider the full suite of cultural, mechanical, and *herbicidal* options available for effective weed control.

Johnsongrass (*Sorghum halepense*), courtesy of
the U.S. Department of Agriculture, Agricultural Research Service (Barry Fitzgerald).

Addressing the Pressing Problem of Herbicide Resistance

Harold Coble
U.S. Department of Agriculture, Agricultural Research Service

This presentation is a discussion of how to address the problem of herbicide resistance, not from a technical perspective, but from a human perspective. Herbicide-resistant weeds are a game changer for agriculture just as drug-resistant microbes have been a game changer for the health care industry. Weed *control* today is chemically based. The reason nearly 100 percent of row crops are treated with herbicides is because nothing else comes close to the effectiveness and efficiency of herbicides in killing weeds over a wide area. Good weed *management*, on the other hand, involves the integration of many practices within the strategic approaches of prevention, avoidance, monitoring, and suppression. From the management perspective, one must assume that all fields have resistance present. That resistance may not have manifested itself yet in an actual plant and may not have been selected for yet, but because genes have many ways of moving around, proper management dictates that assumption. Weed resistance is an area-wide issue because of the propensity of weed resistance genes to move with ease from field to field. In the past, the next new chemical in the pipeline was used to solve resistance problems—no more. New mechanisms of action are not forthcoming in the near future, and a better job of integration must occur to preserve those valuable control tactics presently available. Successful systems in the future will be more management-intensive and involve more diversity of tactics. A mindset change may be necessary to fully incorporate these new, successful systems.

KEY POINTS

- *Managing resistance requires a new mindset!*
- Herbicide-resistant weeds are a game changer for agriculture just as drug-resistant microbes have been a game changer for the health care industry.
  - They have occurred with multiple classes of chemistry.
  - They have evolved because of complacent management.
  - Managers need to be more observant and disciplined to avoid this problem.
- The technology is not to blame—problem is based on how the technology was used.
- All actors in the system (university, industry, agency, dealers, farmers) are to blame for the problem.
  - They ***must*** work together to find and implement solutions; only then can *preparation meet opportunity.*

Kochia (*Kochia scoparia*), courtesy of WildBoar (http://commons.wikimedia.org/wiki/Fille:Kochia_scoparia_02.jpg).

The Impediments to Using Best Management Practices

A panel discussion[1] representing farmers, crop consultants, lenders, and scientists with different perspectives who identified common impediments to shifting to a new weed-management mindset

Ben Barstow, Past-President, Washington Association of Wheat Growers

Herbicide resistance is nothing new. The Pacific Northwest wheat industry experienced the equivalent of glyphosate-resistant Palmer amaranth in the early 1980s in the form of sulfonylurea (SU)-resistant prickly lettuce. In that case, the major registrant of SU herbicides voluntarily changed its labels to require tank mixes with alternate mechanisms of action. That voluntary strategy was able to preserve the effectiveness of SUs for another 20-30 years. Today, however, species that were hardest to control with those tank-mix products 30 years ago are now widely tolerant, if not resistant, to the combinations. I can remember 40 years ago, when my grandfather's primary weed control relied on mechanical cultivation. His worst weed problems were deep-rooted perennials, species most adapted to repeated tillage in our climate of dry summers. My point is strict reliance on *any* single control method, be it a class of chemistry or even mechanical tillage, eventually will select for a population that overcomes that control method. Further, this process happens just as readily in the absence of herbicide-resistant, genetically engineered crops as it does when their use is widespread.

One key to combating resistance is to keep as many strategies available as possible and to change strategies frequently. We have not done a very good job of that. Our toolbox for managing resistance has fewer tools than it once did, and new tools have become rare. Registrations of older chemistries are difficult to profitably maintain, and the flow of new chemistry has almost stopped. Regulators have targeted whole classes of chemistry for cancelation. Farm bill conservation strategies have encouraged farmers to eliminate tillage as an option to the point that many farmers no longer have the equipment to consider that option. Market forces sometimes discourage crop rotation, and farmers, after all, are human; if a control strategy is available, cheap, and effective, we will use it until it doesn't work anymore.

---

[1]Ken Root ably moderated this panel.

Chuck Farr, Crop Consultant, Mid-South Ag Consultants, Inc.

Q: Why do growers resist using best management practices for herbicide-resistant weeds?

A: I think this has many answers, but one of the major concerns is from the crop insurance industry. Growers who insure their crops or some who are just "insurance farmers" will plant a crop and put the least amount of inputs into a crop whether they have resistant weeds or not. They know that they are getting paid on yields or income and not on how well they manage resistant weeds. Therefore, they have no concerns for resistance. Also, there are still a small group of growers who think resistance is not on their farms. This is a small number, but there are still a few around.

Q: Do consultants make recommendations on best management practices or the one that has the easiest convenience?

A: I really think that all consultants make recommendations based on best management practices. Now there may be many choices in the best management practices, and we all tend to make the most logical recommendations based on mixing ability of herbicides or the pounds of material that may be used or ones that have rotation restrictions, but best management practices are a large part of our business.

Q: Are there recommendations you make that growers are particularly resistant to?

A: We do make recommendations that growers are resistant to. Generally these recommendations require more money than they budgeted for, an extra trip across the field, a product that requires a large amount of water during application, or an application that requires water or rainfall for activation. Growers do want to resist some recommendations, but they always make the recommended applications because they know the consequences if they do not.

Q: Where do you get your information about best management practices? Where do crop consultants get their information in general?

A: We get most of our information from other consultants in the business, from all university programs, from basic manufacturers' development trials, and from our on-farm trials. We look for trends in what works and what does not. We feel very comfortable with the science that we have to make recommendations. The major problem that we have is the lack of currently available products and the lack of products in development that we have to choose from. We are very limited in our product selection with weed resistance.

David Miller, Director of Research and Commodity Services, Iowa Farm Bureau Federation

I farm approximately 550 acres (corn-soybean rotation) in the central part of southern Iowa. As far as I know, I do not have a problem with herbicide-resistant weeds on my farm. Some of the management practices that I use to minimize the risk of weeds developing herbicide resistance on my farm include regular crop rotation, use of multiple herbicide technologies, and avoidance of "half-rate" applications.[2]

But the question to be addressed is, "What are the impediments to using best management practices?" I believe the primary impediment is the near-term costs associated with implementation of best management practices to forestall a problem that may or may not develop at some unspecified time in the future. The corn seed I buy often has multiple stacked traits. Imbedded in the cost of that seed are technology fees for these traits. I pay those fees even if I choose to use a different herbicide and not use the herbicide-resistant trait incorporated into the seed. I do this because I want (or need) the other traits contained in the stack, but the choice to not use the herbicide-resistant trait can result in a $15 to $20 per acre increase in my herbicide costs in those years when I use alternative herbicide technologies.

The second most important deterrent to implementing best management practices with respect to minimizing herbicide resistance in weeds is strict adherence to no-till production practices. Eliminating tillage from the production protocol increases reliance on post-emergence herbicides and, realistically, on glyphosate-based formulations.

There are other impediments to using best management practices for managing herbicide resistance in weeds. They include weather-induced delays that can result in untimely herbicide applications, monoculture crop rotations due to dominant economics for that particular crop, and the "ease" of using a single herbicide technology across multiple crops, rotations, and geographies.

Steve Reeves, Vice President, Bank of Fayette County

Lending institutions have to be careful as to how they guide producers because of lender liability laws. I encourage best farm practices such as rotation, mowing end rows before weed seeds mature, and applying recommended herbicide application rates. As I perform preseason cash flows, all formulas are based on the recommendations. Any variance could result in changes in the net income to the producer. I do see the possibility of herbicide-resistant weeds adding to the variable cost (e.g., labor, fuel, and herbicide) in the future as farm margins are narrowing.

Dale Shaner, U.S. Department of Agriculture, Agricultural Research Service

The major impediment to using best management practices from an industry point of view is the difficulty in coordinating recommendations except in general terms. The

[2]Half-rate application refers to using less than the amount of herbicide recommended on the label instructions.

Herbicide Resistance Action Committee, which is a committee of technical representatives from the major agrichemical companies, was created in the 1980s to deal with the rising problems of resistance to ALS and ACCase inhibitors as well as the more established triazine resistance. This committee, of which I was the chair for four years, was and still is very active in developing and publishing guidelines on managing herbicide resistance and in creating and supporting a web-based database on the instances of herbicide-resistant weeds. However, this committee is confined to technical issues and for legal reasons does not get involved in marketing issues. Industry has been criticized for acting too slowly when resistance is selected for new mechanisms of action, such as the HPPD or PPO inhibitors, but it takes time to really understand the extent of the problem and to determine how to best deal with it. Industry has been very active in urging the maintenance of registration of older herbicides that are vital tools for resistance management. With the advent of widespread glyphosate-resistant weeds, industry also is re-emphasizing the discovery of herbicides with new mechanisms of action. Industry has been supportive of regulations that actually deal with herbicide resistance, such as the addition of mechanism of action group identification to the label, but each company is reluctant to implement new strategies without the participation of all of the companies. Unilateral action can be nonproductive if it is not supported by other companies. This will continue to be an impediment for implementing best management practices and can undermine university and governmental recommendations unless industry is an active participant in developing these practices.

Prickly lettuce (*Lactuca serriola*), courtesy of Stan Shebs (http://commons.wikimedia.org/wiki/File:Lactuca_serriola_3.jpg).

A Social Science Perspective on Weed Management Practices

George Frisvold
University of Arizona

The survey research my colleagues and I have been conducting examines the extent to which growers are adopting different resistant-management best management practices (BMPs). We want to know how often farmers are using these practices. The good news is we found out that most growers were applying most practices most of the time; however, the bad news is that that is not good enough. Many growers are not practicing some very important BMPs. Survey results show that there are many practices that corn, cotton, and soybean growers are using often or always. In fact, there is greater difference across practices than across crops. For example, using different mechanisms of action, cleaning equipment, and supplemental tillage are not widely adopted. The data on cumulative adoption of BMPs—how many growers are adopting how many practices—show that most growers adopt seven or more BMPs often or always. Yet, there are still important BMPs that many people are not using much of the time. From surveys conducted over the last decade we know that many growers have perceptions that discourage BMP adoption. These perceptions include:

- Attribution of spread of resistant weeds to natural forces and neighbors' behavior
- Belief that individual action has little effect on resistance
- Belief that resistance is inevitable
- A low awareness of how practices affect weed resistance
- A low awareness of the importance of rotating herbicides with different mechanisms of action
- A low concern about resistance
- Confidence that new products will become available

From the 2000s to now, the level of concern about resistance seen in the surveys has been ramping up, which may mean the problem is getting worse, though it also may mean that people are more aware of the issue. The surveys tell us that, in terms of research needs, many growers have perceptions that seem to discourage BMP adoption. Therefore, it would be useful to know: How pervasive are these different perceptions, how have they changed since the early- to mid-2000s, and how do these perceptions affect resistance management today?

Extension economists often use partial budgeting (that is, returns per acre) to account for growers' management decisions. However, grower decisions are more complex than that. Decisions depend on nonpecuniary benefits (flexibility, simplicity) to the farmer. Even the direct economic returns are more complex than just a plot level partial budget analysis will show. A model that accounts for the entire household's well-being provides a better picture of what affects grower decisions, because there are several issues in the farm household at play that are not apparent in a simple budgeting approach. Things to account for include:

- How flexible is the management system?
- How much time does the system require?
- How do regulations and incentives on highly erodible land factor in?
- What kind of equipment does the farmer have (i.e., is the equipment needed for some BMPs available)?
- Does the farmer have the knowledge base for a variety of weed control options?
- Are there management constraints or options related to the ownership of the land?
- Is there urban development pressure (affecting a farmer's time horizon)?
- How long does a farmer plan to farm?
- What percentage of household income comes from farming?

Furthermore, the benefits of resistance management to an individual grower are uncertain. There may be benefits in the future, and those benefits may be somewhat dependent on what neighbors do, but the costs are certain. Growers have to weigh these uncertain, future benefits that depend on a whole set of contingencies against direct monetary costs of current actions. To deal with that uncertainty, we may have to move away from just looking at short-run profits to something more in the realm of behavioral economics and collective action to understand people's decisions.

There are useful lessons to be drawn from the Green Revolution about how farmers behave. When the high yield varieties of the Green Revolution became available, they were part of technological packages that depended on complimentary inputs. At the time, it was commonly thought that farmers who did not adopt the new technologies were in some ways "primitive" or "backwards." Study of the constraints that individual farmers were facing in particular countries or with particular crops revealed that farmers had good reasons for why they were not adopting the technology. Looking at the real constraints that people face, failure to adopt may not result from a lack of understanding. Rather, a farmer's immediate survival drives what they do. The studies from the Green Revolution also show that adding uncertainty into the analysis improves the explanatory power of economic models. Introducing uncertainty demonstrated the importance of farm size, credit constraints, infrastructure constraints, and the availability of information and opportunities to learn to determine how people were going to adopt technology. It also showed how and what information is provided to farmers is important. It is important to know from what sources farmers are getting their information, how the information source affects their behavior, and whether farmers are getting a consistent message. Regarding weed resistance management, growers are still getting conflicting messages about the value of certain practices (such as use of below-label rates for herbicides).

There are also lessons to be learned from voluntary environmental programs. The track record of voluntary programs has been mixed, but there are some successes. There is some evidence in the literature that voluntary programs perform better if there is a regulatory option in the background. It might be helpful for extension education to find out what farmers think of particular regulatory options. Growers may respond more favorably to voluntary options if they are made aware that regulatory options are also being considered.

A Miranowski and Carlson paper for the National Research Council's 1984 symposium[1] on strategies and tactics for managing pesticide resistance in insects posed the question: What is the proper division between the public and private sectors regarding resistance management? Instead of assuming resistance is a problem with the private sector that necessarily requires regulation, the paper examined the conditions more favorable to voluntary approaches and those more favorable to regulatory regimes. Looking at the conditions that would predict one or the other, their model successfully predicted why there is a different regulatory system for insect-resistant versus herbicide-resistant crops. They looked beyond farm-level problems and examined the market structure and the pricing of the input supply industries. Input suppliers and growers both want pesticides to stay effective, so they looked at to what extent commonality could be used as a way to structure programs. They also focused on the fact that price is a signal of scarcity. Insecticide prices at the time of the study were not going up relative to other inputs, so the market was not providing growers with any signal that these compounds were becoming scarcer. Applying the same framework today to herbicides, we see that herbicide prices are rising more slowly than most other production inputs, so farmers are not getting any price signal in the market that new technologies are not coming. However, seed markets and chemical markets need to be looked at together because of genetically engineered crops. Seed prices have been going up, so the price of seed may be the signal of scarcity.

The relevant players in improving adoption of BMPs are:

- Growers (large- and small-scale)
- Suppliers of seed, biotechnology, and agricultural chemicals
- Grower associations (national, state, and local)
- Scientific associations
- Weed management consultants and custom applications
- Other custom operations
- U.S. Department of Agriculture (USDA)
- U.S. Environmental Protection Agency

[1]Miranowski J.A. and G.A. Carlson. 1986. Economic issues in public and private approaches to preserving pest susceptibility. Pp. 436-448 in *Pesticide Resistance: Strategies and Tactics for Management*. Washington, DC: National Academy Press.

Each of these groups has different incentives. It is important to figure out whether their incentives for resistance management are compatible and what the economic trade-off is for each group. We know little about the incentives or adoption levels of weed management consultants, custom chemical applicators, custom harvest and other custom operations, and small-scale producers. The susceptibility of weeds to herbicides is a weakest link public good, one whose provision requires the effort and compliance by those least able and with the least incentives to provide it. Smaller-scale producers may have more off-farm responsibilities and may not have the capacity to manage resistance. This is unknown because most of the surveys are based on producers farming more than 250 acres. Growers with less than 250 acres of a crop are 30 percent of corn growers, 23 percent of cotton growers, and 32 percent of soybean growers. That accounts for 15 percent of corn acres, 6 percent of cotton acres, and 18 percent of soybean acres. It is a nontrivial population that we do not know much about.

Another concern is that much of our data on resistance management is quickly becoming dated. There was a relatively large amount of data collected in 2005-2007. However, much has happened regarding resistance problems and resistance awareness since then. We do not know if people are doing anything differently. It would be good to do more work with the USDA's Agricultural Resources Management Survey to test hypotheses about factors encouraging or discouraging adoption, including grower attributes.

The old paradigm is a product-based solution, in which growers were seen as customers who bought products off the shelf. Weed management is simplified as much as possible. The idea is that new products will always solve old problems, and the goal is to keep new products coming down the pipeline. The new paradigm emphasizes systems and science and will rely on people being more engaged as sophisticated crop managers. Growers in this paradigm are active participants who will not only adopt new systems but also educate technology developers. It involves more knowledge about the overall agricultural supply chain, especially the structure, conduct, and performance of input industries.

There is going to be a challenge related to knowledge sharing. If we have a limited number of mechanisms of action and there are not going to be new ones, then we are going to have to substitute information and knowledge for chemical compounds. In order to obtain that information, we need grower participation and input. But growers will be less likely to provide information if they perceive that the result will be more regulatory actions. They need to see a benefit to participating.

KEY POINTS

- ❖ Most growers use most practices most of the time, but that behavior pattern does not promote effective resistance management.
- ❖ Increased adoption of effective best management practices will require that we move beyond a short-run profit maximization model to understand more complex constraints and motivations driving farm household behavior.
- ❖ A new paradigm is needed to understand grower behavior and foster a new mindset—one with greater knowledge of the interplay of agroecological, economic, and social systems.

Lambsquarters, common (*Chenopodium album*), courtesy of the Weed Science Society of America.

What Approaches Are Most Likely to Encourage the Adoption of Best Management Practices?

A panel discussion[1] exploring the incentives needed to improve adoption of better weed-management strategies and to promote the development of new weed-control technologies

Tom Green, President, IPM Institute of North America

The IPM Institute was founded as an independent nonprofit in 1998 to leverage the power of the marketplace to improve environment, health, and economics through integrated pest management (IPM) and other best practices. Located in Madison, Wisconsin, our staff of twelve works in both agriculture and communities (www.ipminstitute.org). Projects include work with major food corporations, schools, municipalities, and the structural pest management industry. Much of our work involves changing behavior. We draw on the science of behavior change including Rogers' theory of innovation adoption. In several projects, we focus on late adopters who potentially are responsible for a large and disproportionate share of the challenges we face in improving sustainability. These late adopters are apparent in weed-resistance management; for example, 28 percent do not use different herbicide mechanisms of action.

Our BMP CHALLENGE collaboration with American Farmland Trust provides both technical assistance and a net income guarantee to corn farmers so that they can experiment with both new and old technology for reducing nutrient and sediment losses from cropland (www.bmpchallenge.org). Farmers work with crop advisors who recommend appropriate practice(s) and carefully set out check strips in enrolled fields. Farmers and crop advisors work together to implement practices and compare yields and net income at harvest. Agflex, a corporation we founded specifically for this purpose, maintains reserves and compensates farmers who have a net income loss (www.agflex.com). Eighty-nine percent of participating farmers change practices for the better as a result of their participation. Perhaps an income guarantee coupled with technical assistance could help farmers use herbicides more appropriately to manage resistance.

[1]Dr. Kitty Smith ably moderated this panel.

We also have been working to more effectively engage crop consultants through programs offered by the Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service. Our national working group, co-led by Michigan State University since 2006, has been increasing participation in NRCS programs for IPM since 2006 (nrcs.ipm.msu.edu). In 2012, NRCS introduced a new IPM option for farmers to hire crop consultants to help prepare a plan to delay and avoid herbicide resistance. NRCS qualifies crop consultants as Technical Service Providers (TSPs), and more are needed. NRCS offers a new, one-day training for those interested in becoming TSPs and recently trained more than 100 consultants in Arkansas to prepare these plans. Financial assistance rates are $1,628 per plan for plans addressing 100 acres or less, and $2,730 for plans covering more than 100 acres.

Another example of innovations with potential applications in managing resistance include a pilot we initiated with collaborators in the Sandusky River Watershed in Ohio. There we are working with agricultural retailers to identify products and services that will reduce phosphorus losses from cropland and clean up the excess phosphorus problem in Lake Erie. Working with eleven retail locations and their farmer clients, we are creating a regional business plan to accomplish this goal. Could we apply this approach to resistant weeds?

Finally, we are working with food companies including Sysco, McDonald's, a major national supermarket chain, and their supply chains to improve sustainability and maintain competitiveness in the face of mounting consumer and shareholder interest in supporting corporations who share their values. Best practices are identified and promoted, and adoption is tracked throughout large supply chains. Adjustments are made to improve adoption in specific focus areas. Managing herbicide resistance could be prioritized in these programs.

John Hamer, Venture Partner, Burrill & Company

Venture Capital and Innovation Investment in Agriculture

- Total venture capital financing is down from its peak in 2000 at $99 billion to approximately $29 billion and continues to slowly decline. Overall venture returns are poor relative to other asset classes, with the 10-year returns falling below 4 percent. The result is that institutional capital is seeking other investment opportunities in alternative asset classes (buy-out, hedge funds, etc.). While there is some concern about this, the United States still leads the world in Venture Capital (VC) funding by a significant margin (around $29 billion) compared to other countries (generally less than $2 billion). Other regions of the world (Asia, Eastern Europe, South America) all see biotechnology and VC as a source of innovation for industry diversification.
- Venture capital investment in the United States is highly skewed geographically, with more than $11 billion being spent in the San Francisco Bay Area (Silicon Valley). A vast majority of the life science VC money goes to healthcare/biotechnology ($5 billion), cleantech (around $5 billion), and internet/telecom/computers ($7 billion).

- Traditionally, agriculture investing has been a very small portion of the life science VC dollars (less than $100 million annually). Despite this, small agricultural biotechnology companies have contributed disproportionately to today's genetic-engineering technologies (herbicide and insect resistance).
- Recently, the rise of "cleantech" investing has increased the interest in agricultural biotechnology. Cleantech investing includes areas such as sustainability, food security, water, and biofuels/biorefining. All these areas have agriculture as a significant player. The recent IPO by Ceres, several recent acquisitions, and a growing interest in the needs for improved agriculture have all increased the interest of some VC groups.
- Corporate VC groups have become a much stronger player in funding innovation. Corporate balance sheets are strong and large companies are using VC as part of an innovation strategy. Examples in agriculture include:
    1. Monsanto recently announced an alignment with Atlas Ventures in Boston as well as its investments in Nidas Capital.
    2. Syngenta has a new venture fund based in Research Triangle Park, North Carolina, and a previous $100 million commitment to LSP Bioventures in Boston.
    3. Dow Agrosciences recently started a New Ventures group, and Dow Ventures has dedicated agriculture resources.
    4. BASF ventures has become more active in renewable energy, providing $40 million to Renmatix, a company that converts biomass into sugars.
    5. BP Ventures has made investments in agricultural biotech companies Chromatin and Mendel.
- Several factors are contributing to some life science funds looking more closely at agriculture investments. These factors include: the need for more food and protein globally, increasing commodity prices, and the role of agricultural feedstocks in bioprocessing and biorefinery endeavors. New funds include:
    1. First Green Partners—$350 million (Doug Cameron and Warburg Pincus).
    2. Cultivian (Ron Muessen focusing on the Midwest).
    3. Finistere Partners (Jerry Caulder with funding from New Zealand).
    4. Physics Ventures, DBL, Venrock, Mayfield, and Polaris continue to be interested in agriculture.
    5. New agriculture investments include NexSteppe and IPOs by Ceres. Acquisitions of Divergence and Pasturia (for new nematicides) as well as last year's acquisition of Athenix by BayerCropScience are examples of continued interest in the area.
- Specifically related to pesticide research, the major agricultural chemical companies are still the drivers of innovation, primarily due to their significant in-house expertise, infrastructure for chemical process development, and deep grower relations. New trends include increased innovation around seed coatings, new herbicide resistance genes for dicamba, 2,4-dichlorophenoxyacetic acid (2,4-D), and HPPD inhibitors.

- Several small agbiotech companies are developing "biologics" that are of increasing interest to the majors. These products are considered "natural" and thus are cheaper, easier to register, and can be used in IPM strategies. Several biologics companies have acquired assets in this area and have targeted biologics as an area for growth.

John Soteres, Chair, Herbicide Resistance Action Committee

The Herbicide Resistance Action Committee is the industry stewardship group focused on weed resistance to herbicides and best practice strategies for resistance management. Our purpose and goal is to further the science related to weed resistance and to provide product stewardship through the development, promotion, and adoption of best management practices. Herbicide resistance is not new. Resistance is a challenge for all herbicides and concerns all sectors of the agricultural community. What's different today is a greater understanding of this challenge and broader appreciation of the need to implement more diversified management strategies. Management strategies must be effective, reliable, practical, and economical, and these strategies must then be communicated to farmers together with the benefits of adopting these practices on the farm. With weed-management practices, our task is to convey the long-term benefit of more sustainable integrated practices in contrast to the visible short-term benefits of practices that seem effective today.

We are making progress, and the agricultural productivity industry is committed to furthering this progress in cooperation with academics, commodity groups, government agencies, and others. The industry is offering financial and nonfinancial incentives to farmers in support of more diversified and integrated weed management programs. Market research indicates that these incentives are contributing to a positive trend toward increased diversification. The path forward will not be without challenges, but it is possible to drive further improvements in weed resistance management through sustainable diversified practices that fit with our best science by:

1. Increasing and improving training and education efforts with a focus on proactive implementation of diversified management.
2. Offering financial incentives, as appropriate, to encourage use of best management practices.
3. Increasing weed-management options that will lead to increased diversity through industry-directed chemical and biotechnology research.
4. Funding basic and applied research into herbicide and nonherbicide options in conjunction with other sources.
5. Increasing product delivery options, such as herbicide premixes, as a way to address cost and convenience barriers to adoption of best management practices.

The Herbicide Resistance Action Committee and the companies it represents are committed to active stewardship of our herbicide resources and stand as a ready partner with the public sector to further our common goals.

Paul B. Thompson, Michigan State University

Process Standards for Resolving Resource Conservation Dilemmas

Although they go by different names, many challenges in natural resource management have the general structure of collective action problems. A beneficial result can be achieved if everyone (or nearly everyone) defers some short-term benefit associated with resource exploitation and engages in use patterns that conserve the resource over the long term. These are not cases where individuals must permanently sacrifice self-interest for some larger cause. Every party will enjoy greater benefit if conservation is effective, so cooperation is consistent with self-interest. But in the absence of cooperation, each individual has strong incentives to engage in exploitive use. The policy challenge is to get the cooperative behavior up and running so that the collective benefits can be realized and then to ensure that people keep cooperating in the face of opportunities to gain advantages by defecting from the cooperative scheme. These challenges have been variously described as the tragedy of the commons, common-pool resource management, and free-rider problems.

The susceptibility of weeds to herbicides can be conceptualized as just such a problem if several conditions are satisfied. First, there must be patterns of herbicide use that would either prevent or substantially delay the emergence of resistant plants. Such patterns of use must be effective enough in controlling weeds to make them worth doing. Second, users of herbicides must stand to benefit over the long run if susceptibility is maintained or the onset of resistance is delayed. The most likely long-term benefit is simply the ability to continue to use a cost-effective weed control method that has acceptable environmental and health risks. Finally, there must be reasons users would not utilize the conservation strategy. Such reasons may be complex. Farmers may doubt the effectiveness of the conservation strategy, perhaps because they doubt others will comply. Hence, they hope to extract maximal short-term benefit before the effectiveness of the herbicide is lost. However, reasons may also be simple: They may not understand that the conservation strategy is in their self-interest or may think that it is inconvenient to follow. The following discussion illustrates some generalized responses to collective action problems and does not undertake detailed discussion of the biological strategies for controlling herbicide resistance or the human reasons for failing to deploy such strategies given current policies.

When ecologist Garret Hardin published his widely read article on “the tragedy of the commons” in 1968, the general thinking on collective action problems held that in the absence of means to privatize the resource in question, the only solution to them was government intervention. Interventions might take the form of coercive regulation or incentivizing compliance through subsidy, but the power of self-interest was believed to be so overpowering that individuals acting on their own could never develop a means to bring about or maintain cooperative conservation (Olson, 1965). Work by economists and political scientists has since documented a wide variety of ways in which groups have brought about effective responses to the need for cooperative conservation. A detailed discussion of the new theory of common-pool resource management is beyond the scope of the present discussion. Responses generally combine ethics, understood as a means of mutually recognizing the value of conservation and reproducing cultural norms dedicated to its continuation, with monitoring and enforcement mechanisms that draw on culturally robust institutions of duty, guilt, and shame, as well as more conventional penalties (such as fines or denial of access to the resource) for defection (Ostrom, 2008, 2009).

Such informal governance mechanisms have been especially effective where the resource to be conserved is coextensive with a geographically contiguous region such as a forest, a fishery, or a watershed. Spatial contiguity facilitates both the formation of a local culture and the group-monitoring activities that are needed to enforce norms. It is not clear that management of herbicide resistance will lend itself to such informal mechanisms. However, another type of mechanism has evolved that exploits the organization of food system supply chains as they currently exist in highly industrialized and global markets. These mechanisms involve tripartite standards regimes that include mechanisms for the creation, certification, and accreditation of process standards for food and fiber products produced on commercial farms (as well as some manufactured goods) and traded on national and global markets. The picture will become clear as a few of these key terms are defined and some examples are given.

Grades and standards for agricultural products traditionally have been associated with product quality. Product standards, such as the USDA grading criteria for meats, were developed to organize markets but were based on observable features of the final product. Standards for food safety were based on identification of tolerances for potential contaminants, trace chemicals, or microorganisms and were similarly based on scientifically observable characteristics of a product. In contrast, a *process standard* is based on characteristics of the production process not detectable through close observation or testing of the product. Key process standards that have emerged over the last 20 years include "fair trade," "GlobalGAP," and various standards for the humane treatment of food animals. The most influential process standard is "organic" or "bio," which stipulates a number of specific production practices that must be followed before products can be marketed under the corresponding label (Busch, 2011a).

Both product and process standards involve the interaction of three activities. First, there must be bodies or organizations that develop the standards in question. It is not unusual for multiple standards to emerge from competing standards developers. Second, there must be a method for certifying that products, processes, or both are in compliance with the standard. Classic product standards are certified by inspection or scientific test applied directly to the product, while process standards more typically are certified through inspection of the production process along with record-keeping methods (themselves the focus of process inspections) to ensure that products indeed have been produced according to the specifications of the standard in question. Finally, certifiers themselves must be accredited. Accreditation ensures that certification methods and practices provide reasonable assurance that standards have been interpreted accurately and provides a mechanism for ensuring that conflicts of interest do not undermine the entire purpose of standards implementation. The interlocking activities of standards development, certification, and accreditation create a self-reinforcing network of organizations and activities. This network constitutes a *tripartite standards regime* (Stone et al., 2012).

Tripartite standards regimes may involve government agencies in all or part of their activities. In the case of the USDA organic standard, standards development was undertaken under the auspices of the USDA Agricultural Marketing Service. However, producers wishing to participate in the National Organic Program must contract with a private certifying agent. These agents may be nonprofit organizations, though they tend to be for-profit firms. Certifying agents in turn are accredited by USDA. Thus, in the case of the U.S. organic standard, the government operates two of three components of the tripartite standards regime. Furthermore, farmer participation in the program is entirely voluntary and may be motivated by profit or by other personal goals. The National Organic Program was developed at the request of growers who hoped to simplify access to what they perceived to be an important market opportunity (Guthman, 2004). Although the National Organic Program is the most successful example of a current process standard, it may not be a particularly apt model for approaching the dilemmas of herbicide resistance. However, other process standards that have emerged in the food system illustrate this potential.

Fair Trade. The term "fair trade" is used generically to indicate a number of specific standards intended to return a larger share of the final consumer price of agricultural commodities to primary producers. FairTrade is a term licensed by the Fair Trade Foundation, a nonprofit organization based in the United Kingdom that was established with the goal of helping small-scale producers, especially in the developing world. The Fair Trade Foundation initially developed the standards for use of the FairTrade label and served as a certification body. Now, standards development and accreditation have been ceded to a consortium of fair trade labeling organizations including Fair Trade International, while the Fair Trade Foundation concentrates on certification and market development. Literally dozens of similar standards have been associated with terms such as "equal exchange," "social accountability," and "Oxfam" (the name of a well-respected nongovernmental organization), each of which is associated with a similar tripartite standards regime.

Fair trade standards are worth noting in part because they operate almost entirely outside governmental authority. Key actors are primarily not-for-profit charitably oriented organizations, many of which have been formed with the express purpose of promoting fair trade. As with the organic standard, participation by producers is entirely voluntary. The primary incentive for participation by producers is economic. The effectiveness of the standard depends on purchase behavior by consumers. If enough consumers can be enrolled, the fair trade standard becomes an effective way to return a larger share of consumer price to producers. However, consumer confidence is undermined when fair trade-type labels are deployed without adequate procedures for certification. Debates over the effectiveness of fair trade have led some to suggest that accreditation of certifiers, at least, should fall under the authority of a legally constituted government agency. Indeed, the United Nations Conference on Trade and Development (UNCTAD) has reviewed a number of fair trade schemes, identifying dozens that they believe accomplish fair trade objectives. UNCTAD stops short of recommending state-supervised accreditation. Compared to other standards reviewed here, fair trade is still the Wild West of tripartite standards regimes.

Sustainability. There are a number of efforts to develop process standards focused on sustainability, both within the food system and more generally. The International Organization for Standardization (ISO) has a general sustainability standard (20121) in development. Other examples do not use the word sustainability but are intended to promote environmental or social improvement while restructuring supply chains. Formerly known as EuropGAP, GlobalGAP is a set of common agricultural production process standards that are being developed by a consortium of European supermarket chains. It is but one of many efforts to develop standards under a broad "green" or sustainability umbrella. When complete, the content of GlobalGAP standards will be a set of good agricultural practices covering food safety, worker health, food quality, and environmental impact of production processes. The supermarket industry hopes that compliance with these standards will assure customers that they are working to achieve sustainability throughout the food system. The eventual goal is for all products sold in member stores to comply with GlobalGAP standards. As with USDA Organic, certification will be done by an independent organization or firm. Accreditation of these certifying agents will take place under the auspices of mostly government-supervised accreditation agencies in the respective countries where members of the consortium source products to be sold under the GlobalGAP standard. The relevant body in the United States is the American National Standards Institute, a private, not-for-profit organization that includes U.S. government agencies as members and is the official U.S. government representative to the ISO.

Like all sustainability standards developed to date, producer participation in GlobalGAP is technically voluntary. But to the extent that these standards become requisite for one's products to appear on supermarket shelves, producers selling into commodity markets may find themselves with little choice but compliance. It is thus clear that *if* GlobalGAP decided to institute herbicide management procedures into its good agricultural practice requirements, this particular private process standard would very likely become even more effective than mandatory federal regulation in incentivizing rapid change in farmer behavior (Loconto and Busch, 2010). GlobalGAP or other standards would be instituted by downstream actors in the supply chain in order to bolster consumer confidence or to burnish their image as a "green" company. However, because of the power associated with integrated access to the processing system or retail markets, this standard would rapidly convert the idealized form of producer compliance into a reality (Busch, 2011b).

Animal Welfare. As with other areas reviewed above, process standards intended to address the welfare and well-being of agricultural animals are being developed under a number of distinct tripartite standards regimes. State agencies have been the primary actors in the European Union, though a number of retailers have attempted to establish standards for premium products that could be offered at higher prices. Nongovernmental organizations (NGOs), such as the American Humane Association, have been active in the United States, but an effort by a producer organization, the United Egg Producers (UEP), is of particular interest. Following an action by the McDonald's corporation in 1998 requiring egg suppliers to meet standards for hen welfare that had been developed by an independent committee of experts, UEP convened its own scientific committee to recommend standards, which were adopted by the UEP Producer Committee in 2000. At first initiation, the UEP welfare standard primarily addressed space requirements computed on a per-bird basis, which were increased by nearly 50 percent of typical industry practice at the time. Standards since have been revised and updated to address noncage production systems and other production practices, such as induced molting through feed withdrawal (Mench, 2008).

The UEP standard for hen welfare was voluntary, however. To incentivize compliance, UEP developed a label, eventually call "UEP Approved," which could only be applied to eggs produced in compliance with the standard. Certification was undertaken by both USDA inspectors and private certifying firms. Accreditation of certifiers is currently done by UEP executive officers with advice. Although consumer awareness of the UEP Approved label remains low, several retail chains have adopted policies of stocking only UEP-certified products. The result has been rapid and widespread compliance within the egg industry. In a personal communication, UEP President Gene Gregory reports that uptake was rapid, covering 80 percent of the industry within two years of adoption by the UEP Producer Committee, and participation has continued to increase in the intervening years.

The UEP's effort is interesting in the present context because it represents an initiative undertaken by a producer organization, though as with GlobalGAP a significant additional incentive for participation in the standard accrues from its use as a requirement for entry into key retail markets. However, the fact that the standards process was begun by and remains controlled by producers shows that standards processes can be driven by any of several actors in the supply chain: producers, consumer-oriented NGOs (as in the case of free trade), or retailers (GlobalGAP). Thus, there are significant options beyond the case of government regulation to bring about means for addressing collective action or common-pool resource dilemmas.

Like the common-pool resource management schemes for fisheries, forests, and other classic instances of natural resource conservation, tripartite standards regimes can be effective nonstate means of soft law—the domain where social expectations and voluntary mechanisms create incentives and penalties that rival the power of governments for influencing human behavior. Ethics, understood to include the give-and-take of opinion and debate that creates and reinforces such expectations, is a crucial component of that process. If an ethically convincing rationale emerges linking conservation of herbicide effectiveness to sustainability, it could be possible for retailers or other actors within the food and agricultural products industries to put process standards in place that virtually force producers to comply. If producers not only come to understand that they would benefit from compliance with herbicide conservation strategies, but they should act collectively to do so, the opportunity for effecting a tripartite standards regime to bring this about might well arise within the industry. In the spirit of democracy and participation, the latter approach is preferable.

References

Busch, L. 2011a. Standards: Recipes for Reality. Cambridge, MA: The MIT Press.

Busch, L. 2011b. Food standards: The cacophony of governance. The Journal of Experimental Botany 62:3247-3250.

Guthman, J. 2004. Agrarian Dreams: The Paradox of Organic Farming in California. Berkeley: University of California Press.

Hardin, G. 1968. The tragedy of the commons. Science 162:1243.

Loconto, A. and L. Busch. 2010. Standards, techno-economic networks, and playing fields: Performing the global market economy. International Journal of Political Economy 17:507-536.

Mench, J. 2008. Farm animal welfare in the U.S.A.: Farming practices, research, education, regulation, and assurance programs. Applied Animal Behavior Science 113:298-312.

Olson, M. 1965. The Logic of Collective Action: Public Goods and the Theory of Groups. Cambridge, MA: Harvard University Press.

Ostrom, E. 2008. The challenge of common-pool resources. Environment 50(4):9-20.

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325:419-422*.*

Stone, J.V., A. Loconto, and L. Busch. 2012. Tri-partite standards regime. Wiley-Blackwell Encyclopedia of Globalization*.*

Michael Walsh, Research Associate Professor, University of Western Australia

I'd like to relate a recent experience I had involving extension and adoption. We recently ran a series of workshops in Eastern Australia to communicate harvest weed-seed control techniques developed in Western Australia, which has a larger weed-resistance problem. Along with researchers such as myself, we invited three farmers to present at the workshops. Each had adopted a different form of harvest weed-seed control in Western Australia: chaff cuts, narrow-windrow burning, and the Harrington seed destructor. At the workshops, it was quickly apparent that growers did not want to hear about research results; they just really wanted to hear about the practical experiences the three growers had had in using these technologies. The farmers in Eastern Australia wanted to use them and were ready to adopt, but listening to presentations on the results was not enough to convince them. They wanted to hear how they could set up these systems in their own farms and what it actually meant to their farming systems if they did take on these technologies. The workshops went on for two weeks. Two months later I was back in these same areas setting up harvest weed-seed control trials, and the number of fields I saw that were set up for windrow burning or that had chaff cuts in them was just staggering. There were literally hundreds of thousands of acres that had been transformed and set up for taking on those practices. Because of this widespread adoption, we have had to modify our approach to try to support the growers who have taken up these technologies so quickly. We need to subsequently support them in making sure they get those practices right.

Russian thistle (*Salsola tragus*), courtesy of Stan Shebs (http://commons.wikimedia.org/wiki?File:Salsola_tragus_2.jpg).

The Land-Grant Approach

Steven Leath
Iowa State University

Land-grant universities were born of necessity more than 150 years ago to support the modern agricultural and industrial age. Among their unique responsibilities were: opening the doors of higher education to all, regardless of race, gender, or social or economic class; conducting practical research to meet the needs of the people of the states they serve; and helping people put this knowledge to use to create economic opportunity and improve their communities and their quality of life. Many of the needs and problems of society cannot be solved by any one discipline or any one entity; success means partnerships and diverse expertise. A modern land-grant approach with teams across disciplines and partners from universities, government, and the private sector working together is needed to deal with complex problems. This modern land-grant approach to research and outreach has worked especially well in helping agriculture become much more efficient, productive, and environmentally friendly, and we should continue to look to this model to meet the new challenges faced by production agriculture, such as weeds that are becoming more and more resistant to herbicides.

Ragweed, common (*Ambrosia artemisiifolia*), courtesy of the Weed Science Society of America.

Appendix A

Summit Agenda

A NATIONAL SUMMIT ON STRATEGIES TO MANAGE HERBICIDE-RESISTANT WEEDS

Thursday, May 10, 2012

Jack Morton Auditorium, George Washington University
Washington, DC

8:00	Registration
8:30	Welcome Dr. Charles Arntzen, Florence Ely Nelson Presidential Endowed Chair, Arizona State University
9:00	Herbicide resistance in weeds: What is the nature of the problem? Dr. Micheal Owen, Professor of Agronomy, Iowa State University
9:30	The epidemiology of herbicide resistance Dr. Jodie Holt, Professor of Plant Physiology, University of California-Riverside
10:00	Combating the problem: Australia's experience with herbicide resistance Dr. Michael Walsh, Research Associate Professor, University of Western Australia
10:30	Break

11:00	Best management practices to control and combat resistance Dr. David Shaw, Vice President for Research and Economic Development, Mississippi State University
11:30	Addressing the pressing problem of herbicide resistance Dr. Harold Coble, Agronomist, U.S. Department of Agriculture, Agricultural Research Service
12:00	Lunch
1:15	The impediments to using best management practices Moderator: Mr. Ken Root, Root Communications Panel: Mr. Ben Barstow, Past-President, Washington Association of Wheat Growers Mr. Chuck Farr, Crop Consultant, Mid-South Ag Consultants, Inc. Mr. Dave Miller, Director of Research and Commodity Services, Iowa Farm Bureau Federation Mr. Steve Reeves, Vice President, Bank of Fayette County Dr. Dale Shaner, Plant Physiologist, U.S. Department of Agriculture, Agricultural Research Service
2:45	A social science perspective on weed management practices Dr. George Frisvold, Professor of Agricultural and Resource Economics and Extension Specialist, University of Arizona
3:15	Break
3:30	What approaches are most likely to encourage the adoption of best management practices? Moderator: Dr. Kitty Smith, Vice President of Programs & Chief Economist, American Farmland Trust Panel: Dr. Tom Green, President, IPM Institute of North America Dr. John Hamer, Venture Partner, Burrill & Company Dr. John Soteres, Chair, Herbicide Resistance Action Committee Dr. Paul Thompson, W. K. Kellogg Chair in Agricultural, Food and Community Ethics, Michigan State University Dr. Michael Walsh, Research Associate Professor, University of Western Australia
5:00	The land-grant approach Dr. Steven Leath, President, Iowa State University
5:30	Reception

Appendix B

Planning Committee Biographies

Dr. Charles J. Arntzen was appointed to an endowed chair at Arizona State University in 2000. Previously, he had served as President and CEO of Boyce Thompson Institute—a not-for-profit corporation affiliated with Cornell University. He also served as Director of Research at the DuPont Company; as Director of the MSU-DOE Plant Research Laboratory at Michigan State University; and as Deputy Chancellor for Agriculture and Dean, College of Agriculture and Life Sciences, and Director of the Texas Agricultural Experiment Station in the Texas A&M University System. He was elected to the National Academy of Sciences in 1983. He is a Fellow of the American Association for the Advancement of Science, received the Award for Superior Service from the U.S. Department of Agriculture, served as Chairman of the National Biotechnology Policy Board of the National Institutes of Health, and served for eight years on the Editorial Board of *Science*. From 2001 to 2009, he was a member of President George W. Bush's Council of Advisors on Science and Technology, and from 2004 to 2009, he served on the National Nanotechnology Oversight Board. Dr. Arntzen's private-sector service includes membership on the Board of Directors of several companies, including DeKalb Genetics (prior to sale to Monsanto). He currently serves on the Board of Directors of Advanced BioNutrition, Inc. and is on the Advisory Boards of the Burrill and Company's Agbio Capital Funds and The Nutraceuticals Fund.

Dr. Harold D. Coble is an agronomist and weed scientist with the U.S. Department of Agriculture (USDA) Office of Pest Management Policy (OPMP). In this position, he serves as the Weed Science Liaison with the U.S. Environmental Protection Agency, working on herbicide tolerance reassessments, registration and re-registration, and pest resistance management. He also serves as the Integrated Pest Management (IPM) Coordinator for OPMP and as Chairman of the Federal IPM Coordinating Committee. Dr. Coble was a weed science professor in the Crop Science Department at North Carolina State University for 30 years before taking the USDA position. His research interests included weed biology and ecology, economic threshold development, and management of weed resistance to herbicides. He is a member of the Southern Weed Science Society, the Weed Science Society of America (WSSA), and the Council for Agricultural Science and Technology (CAST), and he served as President of both WSSA and CAST. Dr. Coble is a native of North Carolina and holds B.S. and M.S. degrees from North Carolina State University in Crop Science and a Ph.D. from the University of Illinois in Agronomy.

Dr. David Ervin is Professor of Environmental Management, Professor of Economics, and Fellow of the Institute for Sustainable Solutions at Portland State University. He teaches courses in the economics of sustainability, business environmental management, and environmental and ecological economics. His research program includes genetically engineered crops and agricultural sustainability, university-industry relationships in agricultural biotechnology, ecosystem service management, and business environmental management. He is the Principal Investigator of "Ecosystem Services for Urbanizing Regions," an Integrated Graduate Education, Research, and Training (IGERT) program and Co-principal Investigator of "Spatially-Explicit Assessment of Ecosystem Services Shifts under Climate Change," both funded by the National Science Foundation. Recent publications include "The Theory and Practice of Genetically Engineered Crops and Agricultural Sustainability," in *Sustainability*; "Valuing Ecological Systems and Services" in *F1000 Biology Reports*; "Academic-Industrial Relationships, Academic Scientists' Values, and Agricultural Biotechnology" in *Research Policy*; and "Are Biotechnology and Sustainable Agriculture Compatible?" in *Renewable Agriculture and Food Systems*. Prior appointments include Professor and Head of Agricultural and Resource Economics at Oregon State University, Professor of Agricultural Economics at the University of Missouri-Columbia, Chief of Resource Policy Branch in the USDA Economic Research Service, and Director of Policy Studies for the Henry A. Wallace Institute for Alternative Agriculture. Dr. Ervin also recently was Chair of the National Research Council (NRC) Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability. He holds B.S. and M.S. degrees from The Ohio State University and a Ph.D. from Oregon State University.

Dr. Jodie S. Holt is Professor of Plant Physiology and recent past Chair of the Department of Botany and Plant Sciences at the University of California, Riverside (UCR). She received her B.S. degree in Botany from the University of Georgia and her M.S. and Ph.D. degrees in Botany from the University of California, Davis. Her research focuses on physiological and population ecology of invasive exotic weeds in wildlands and agricultural weeds in croplands, and ecological approaches for weed management and habitat restoration. She is co-author of *Ecology of Weeds and Invasive Plants: Relationship to Agriculture and NaturalResource Management* (3rd edition), which was released in 2007. Holt is an elected Fellow of the American Association for the Advancement of Science and the Weed Science Society of America, where she is also an Associate Editor of the journal, *Invasive Plant Science and Management,* and has served in various leadership roles. She has been Principal Investigator on federal, regional, and statewide extramural grants and served as Panel Manager for the USDA National Research Initiative and Agriculture and Food Research Initiative Competitive Grants Programs. She teaches both graduate and undergraduate courses at UC Riverside and in 2008 won the UCR Distinguished Teaching Award. More recently, she has been involved in Science, Technology, Engineering, and Mathematics outreach programs for K-12 students in the southern California area. In 2010, the San

Diego Botanical Garden awarded her the Paul Ecke, Jr. Award of Excellence for her work promoting plants and conservation.

Dr. Terrance Hurley graduated with a Ph.D. in Economics from Iowa State University in 1995. He is currently Associate Professor in the Department of Applied Economics at the University of Minnesota, where his primary research interest is the profitability, risk, and regulation of genetically engineered crops. He was one of the first agricultural economists to quantify the tradeoffs between the risk of insect resistance to Bt toxin and the long-term productivity of Bt corn, which resulted in the 2001 *Outstanding Journal of Agricultural and Resource Economics Article* award. He has worked closely with the U.S. Environmental Protection Agency on insect-resistance management requirements for Bt crops including service on two FIFRA Scientific Advisory Panels. More recently, he is among the first agricultural economists to quantify the effect of glyphosate weed resistance on the benefits of the Roundup Ready® weed-management program to farmers and the potential for using herbicide rebates to increase the use of residual herbicides for controlling glyphosate-resistant weeds in the Roundup Ready® weed-management program. He currently serves as Associate Editor for the *American Journal of Agricultural Economics*, *Agronomy Journal*, and *Environmental Biosafety Research* and recently served as Associate Editor for the *Journal of Agricultural and Resource Economics*.

Dr. Raymond Jussaume is Professor and Chair of the Department of Sociology at Michigan State University. His academic degrees are from Southeastern Massachusetts University (B.A., Political Science, 1976), the University of Georgia (M.A., Political Science, 1981), and Cornell University (Ph.D., Development Sociology, 1987), and he served as a Peace Corps volunteer in the Republic of Niger from 1978 to 1980. Most of his scholarship falls within the general theme of development sociology, with a particular emphasis on sustainable development. Dr. Jussaume also has academic interests in the sociology of community and of agriculture. He has conducted field research in China, Japan, and France and has extensive experience working on interdisciplinary teams. Some of his more recent work has focused on how the evolution of the interactions between local and global agri-food systems may be affecting sustainable local development. He has published one book, nearly 50 peer-reviewed journal articles and academic book chapters, and numerous bulletins and popular manuscripts that have disseminated the results of his research to citizens. Dr. Jussaume recently served on the NRC Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability.

Dr. Micheal Owen is Associate Chair and Professor of Agronomy and Extension Weed Science at Iowa State University. He has extensive expertise in weed dynamics and integrated pest management and crop risk management. His objective in extension programming is to develop information about weed biology, ecology, and herbicides that can be used by growers to manage weeds with cost efficiency and environmental sensitivity. His work is focused on supporting management systems that emphasize a combination of alternative strategies and conventional technology. Dr. Owen has published extensively on farm-level attitudes toward transgenic crops and their impacts, selection pressure, herbicide resistance, and other weed life-history traits; tillage practices; and many other pertinent issues. Dr. Owen served on the NRC Committee on the Impact of

Biotechnology on Farm-Level Economics and Sustainability. He has a Ph.D. in Agronomy/Weed Science from the University of Illinois.

Dr. Jill Schroeder is Professor of Weed Science and Interim Chair of the Department of Entomology, Plant Pathology, and Weed Science at New Mexico State University, Las Cruces. She earned a B.A. in Biology from Macalester College, St. Paul, Minnesota, an M.S. in Soil Science from the University of Minnesota, and a Ph.D. in Agronomy/Weed Science from the University of Georgia. Her research program concentrates on weed management in irrigated crops with an emphasis on collaborative projects investigating biological interactions among pests and how these pest complexes affect management. She has received a number of competitive grants to support her research and has served on regional and national competitive grant panels, including as Panel Manager for the USDA-Cooperative State Research, Education, and Extension Service National Research Initiative, Weed Biology and Weed Management Program, and Panel Chair for the USDA Agricultural Research Service National Program 304F Peer Review Panel, Office of Scientific Quality Review. Her society memberships include the Weed Science Society of America, serving as Secretary, Vice President, President-elect, President, and Past-President on the WSSA Board of Directors; and the Western Society of Weed Science where she served as Secretary, President-elect, President, and Past-President. Dr. Schroeder is currently serving as the WSSA Subject Matter Expert and Liaison to the U.S. Environmental Protection Agency's Office of Pesticide Programs, Registration Division.

Dr. David Shaw is the Vice President for Research and Economic Development at Mississippi State University (MSU). He began his career at MSU in 1985 as an Assistant Professor of Weed Science. His research focused particularly on optimizing pest management practices to maintain farm productivity while improving surface water protection and management and on development of best management practices for protection of surface waters from pesticides. He has also provided leadership in herbicide-resistance management issues and is participating in one of the largest long-term field projects on glyphosate-resistance management ever established. Because of his developmental efforts in applying spatial technologies to these research areas, MSU appointed Dr. Shaw as the first Director of the Remote Sensing Technologies Center (RSTC) in 1998. The RSTC was merged into the Geosystems Research Institute in 2003, and Dr. Shaw served as its director until his current appointment, which began in January 2010. Honors and awards include MSU's highest distinction as a Giles Distinguished Professor in 1998, the Ralph E. Powe Research Award (MSU's highest recognition for research) in 2000, election as a Fellow in the American Association for the Advancement of Science in 2008, the Outstanding Alumnus Award from Cameron University in 1999, and the Grantsmanship Award from the Mississippi Agricultural and Forestry Experiment Station in 1997. He has received several awards from Weed Science Society of America, including the Research Award, the Education Award, and recognition as a Fellow in the organization. He is the Past-President of the WSSA and currently chairs its S-71 Herbicide Resistance Education Committee and its Task Force on Herbicide Resistance Education. Dr. Shaw also chairs the task force developing the USDA-APHIS report on Herbicide Resistance Best Management Practices and Recommendations and the Council for Agricultural Science and Technology task force on Impacts of Herbicide-Resistant Weeds on Tillage Systems. He is leading the effort to develop a comprehensive suite of educational materials on resistance management based on sound scientific principles. Dr. Shaw received a Ph.D. in Weed Science from Oklahoma State University (OSU) in 1985, an M.S. from OSU in 1983, and a B.S. from Cameron University in 1981.

Appendix C

Speaker Biographies

Dr. Charles J. Arntzen, Florence Ely Nelson Presidential Endowed Chair, Arizona State University (see Appendix B)

Mr. Ben Barstow, Past-President, Washington Association of Wheat Growers
After receiving a B.S. from the University of Idaho and an M.S. from Purdue University, Mr. Barstow spent four years working in cooperative extension and weed science research in Arizona. He was a newly tenured Assistant Extension Professor at the University of Idaho 20 years ago when he "retired" to take the reins of his wife's family's farm in Palouse, Washington. Together with his wife, Janet, Mr. Barstow grows dryland winter wheat, barley, and dry green peas on about 1,000 acres of Palouse silt loam soil in Eastern Washington. Mr. Barstow has served as the Chairman of the Washington Dry Pea and Lentil Commission and is the immediate Past-President of the Washington Association of Wheat Growers. He currently serves as the Research Committee Chairman for the National Association of Wheat Growers. Having worked in sweet corn, soybeans, alfalfa, cotton, and canola, with both insects and weeds, Mr. Barstow has had many opportunities to witness pesticide-resistance disasters. Over the last 20 years as a farmer, he personally understands the economic hurdles farmers face in avoiding those disasters.

Dr. Harold D. Coble, Agronomist, U.S. Department of Agriculture, Agricultural Research Service (see Appendix B)

Mr. Chuck Farr, Crop Consultant, Mid-South Ag Consultants, Inc.
Mr. Farr has been named Consultant of the Year by the National Alliance of Independent Crop Consultants. He has been named Consultant of the Year by Cotton Farming Magazine, an award that is voted on by peers in his field. He specializes in corn, cotton, wheat, soybeans, rice, and milo. Mr. Farr holds a B.S. in Agronomy from the University of Arkansas and an M.S. in Plant Science from Arkansas State University. He has been consulting for 24

years in Northeast Arkansas. He has a wonderful wife Tami and three wonderful boys—Taylor (17), Charlie (12), and Kevin Landry (5).

Dr. George Frisvold, Professor, University of Arizona
Dr. Frisvold is Professor of Agricultural and Resource Economics at the University of Arizona. He received his B.S. and Ph.D. degrees from the University of California, Berkeley. His research interests include domestic and international environmental policy, as well as the causes and consequences of technological change in agriculture. He has been a visiting scholar at India's National Institute of Rural Development, a lecturer at the Johns Hopkins University, and Chief of the Resource and Environmental Policy Branch of USDA's Economic Research Service. In 1995-1996, Dr. Frisvold served as a senior economist for the President's Council of Economic Advisers with responsibility for agricultural, natural resource, and international trade issues.

Dr. Thomas Green, President, IPM Institute of North America
Dr. Green is President and Co-founder of the IPM Institute of North America, a nonprofit organization whose mission is to leverage marketplace power to improve health, environment, and economics in agriculture and communities. The Institute created IPM STAR certification for schools, now impacting more than 2 million children and adopted by the U.S. Army, and offers Green Shield Certification to structural pest management professionals. The Institute is a partner with Sysco on its Sustainable Agriculture/IPM initiative and, with American Farmland Trust in the BMP CHALLENGE project, guarantees farmers income when they adopt conservation practices. Dr. Green and the Institute earned recognitions from the International Integrated Pest Management (IPM) Symposium in 2009 and 2012, and the Institute was recognized as a national award winner in 2004, 2005, 2008, 2009, and 2012 by the U.S. Environmental Protection Agency (EPA) Pesticide Environmental Stewardship Program Champion. Dr. Green is a Certified Crop Advisor, a USDA Natural Resources Conservation Service-certified Technical Service Provider, and a member of the U.S. EPA Pesticide Policy Dialogue Committee and serves as Vice President of the Entomological Foundation. He holds a Ph.D. in Entomology from the University of Massachusetts.

Dr. John E. Hamer, Venture Partner, Burrill & Company
Dr. Hamer's career spans more than three decades of research, senior management, and investment experience in the life sciences. Most recently he spent six years with Burrill & Company, a leading life sciences merchant bank with activities in venture capital, merchant banking, and media. Dr. Hamer was Managing Director and General Partner in several Burrill funds and helped to raise and invest more than $500 million across three funds, including funds based in Latin America and Asia. Prior to joining Burrill & Company, Dr. Hamer was the CSO and later CEO of Paradigm Genetics Inc., a leading genomics and ag-biotechnology company that completed its IPO on NASDAQ in 2000 and was later acquired by Monsanto. Dr. Hamer received his Ph. D. in Microbiology from the University of California at Davis and was a visiting scientist in DuPont's Central Research & Development Group. He later joined Purdue University, where he rose to the rank of full Professor, and was the recipient of several national awards including the David and Lucile Packard Award and the National Science Foundation Presidential Faculty Fellowship. At Purdue, Dr.

Hamer's research focused on crop diseases, where his lab pioneered molecular approaches to disease management and control and worked with numerous international agencies in China, The Philippines, and South America. Dr. Hamer is a passionate believer in the opportunity that is emerging in the agricultural value chain in food, health, energy, materials, and chemicals.

Dr. Jodie Holt, Professor of Plant Physiology, University of California, Riverside
(see Appendix B)

Dr. Steven Leath, President, Iowa State University
Dr. Leath became the fifteenth President of Iowa State University (ISU) in January 2012. Trained as a plant scientist, Dr. Leath served at three universities in teaching, research, and economic development posts en route to the ISU presidency. From 2007 until his appointment at ISU, he served as Vice President of Research and Sponsored Programs for the University of North Carolina system. In the last year, he also served as Interim Vice President for Academic Planning for the 16-campus system. He began his career in 1985 at North Carolina State University's College of Agriculture and Life Sciences, where he progressed through the plant pathology faculty ranks conducting research on disease resistance in grains, primarily wheat and oats, in the U.S. Department of Agriculture's Agricultural Research Service. He was named Research Leader to the unit in 1998, shortly before beginning a stint as the USDA-Agricultural Research Service's acting National Program Leader for grain crops. He returned to NC State in 2001 as Professor and Assistant Director of the North Carolina Agricultural Research Service. He rose to be Director and Associate Dean of the College of Agriculture and Life Sciences in 2005. He was also the Interim Assistant Vice Chancellor for Research prior to his appointment at the University of North Carolina. Dr. Leath holds a bachelor's degree in Plant Science from Pennsylvania State University, a master's degree in the field from the University of Delaware, and a doctorate in Plant Pathology from the University of Illinois.

Mr. David Miller, Director of Research and Commodity Services, Iowa Farm Bureau Federation
Mr. Miller is Director of Research and Commodity Services for the Iowa Farm Bureau Federation (IFBF). In this position, he coordinates the research programs of the Iowa Farm Bureau and the various commodity services offered by the Federation. He provides economic analysis of agricultural issues and is a primary liaison for the Federation with state and national commodity organizations. Mr. Miller has served on several state, regional, and national boards or committees including the National Institute of Animal Agriculture, the Extension Section of the American Agricultural Economics Association, the U.S. Meat Export Federation, the Offset Committee of the Chicago Climate Exchange, the Midwest Governor's Association Greenhouse Gas Accord committee, and the Iowa Climate Change Advisory Council. He joined IFBF in April 1998 as Director of Commodity Services. Prior to IFBF, Mr. Miller served as a commodity policy specialist for the American Farm Bureau, where he worked on agricultural policy issues for dairy, livestock, and the grain industry. He is also active in production agriculture. In 2003, he began active ownership and operation of a 630-acre grain farm in southern Iowa. Primary crops on the farm are corn and soybeans. Mr. Miller grew up on a dairy and grain farm in Indiana with 1,000

acres of crops and 150 dairy cows, which he ran in partnership with his father from 1971 to1984.

Dr. Micheal Owen, Professor of Agronomy, Iowa State University (see Appendix B)

Mr. Steve Reeves, Vice President, Bank of Fayette County
Mr. Reeves was raised and still lives on a multi-generation cattle farm in Fayette County, Tennessee. After receiving a B.S. in Agriculture from the University of Tennessee, he spent four years managing a local COOP. In 1990, he started to work as an agricultural lender for a local community bank. After completing a Masters in Banking from Louisiana State University, he was recruited by another local community bank, Bank of Fayette County, to start an agriculture program. He is a certified F.S.A. lender and works with farmers on a daily basis. He also serves as a Fayette County Commissioner and sits on several agriculture committees. He is active in church work, serving as a Sunday School teacher and Deacon. He and his wife Jeana of 26 years have two children, Shelby and Grace.

Mr. Ken Root, President, Root Communications
Mr. Root is one of America's most recognized farm news broadcasters. He has a 35-year history of covering agribusiness news across the United States and around the world. He travelled with U.S. Secretaries of Agriculture to Asia, South America, Europe, and the Middle East. He also accompanied Iowa Secretary of Agriculture, Bill Northey, to China in 2008. Mr. Root has a broad understanding of agricultural markets and has reported extensively on crops and livestock as well as rural economic development programs in Iowa. He was a finalist in the New York Film Festival for a documentary on Russian agriculture and has won two Oscars in Agriculture for producing the outstanding stories of the year in 1983 and 2008. He received the industry's highest honor by being named Farm Broadcaster of the Year in 2009 by the National Association of Farm Broadcasting.

Dr. Dale Shaner, Plant Physiologist, U.S. Department of Agriculture, Agricultural Research Service
Dr. Shaner was reared on a farm in west central Illinois. He received a B.S. in Botany from DePauw University in 1970, an M.S. in Plant Ecology from the University of Colorado, Boulder, in 1972, and a Ph.D. in Plant Physiology from the University of Illinois, Urbana, in 1976. Dr. Shaner began his weed science research when he was an assistant professor of Weed Science at the University of California, Riverside, from 1976 to 1979. After leaving Riverside, he managed research in herbicides and agricultural biotechnology at the Agricultural Research Center in Princeton, N.J., for American Cyanamid and then for BASF from 1979 to 2001. He was instrumental in discovering the mechanism of action of the imidazolinones and in developing imidazolinone-resistant crops. In 2001, Dr. Shaner joined the Water Management Unit of USDA-Agricultural Research Service in Fort Collins, Colorado, where he conducts research on weed management under deficit irrigation. He helped establish the intercompany Herbicide Resistance Action Committee (HRAC) and was the chairman of HRAC from 1998 to 2001. Dr. Shaner has been active in herbicide-resistance management for ALS inhibitors (imidazolinones, sulfonylureas, etc.) and glyphosate. He developed a leaf disc assay for early detection of glyphosate resistance and

has written several reviews on the impact of glyphosate-resistant crops on selecting resistant weeds and on the mechanisms of resistance to glyphosate.

Dr. David Shaw, Vice President for Research and Economic Development, Mississippi State University (see Appendix B)

Dr. Katherine "Kitty" Smith, Vice President, American Farmland Trust
Dr. Smith is Vice President of Programs & Chief Economist for American Farmland Trust, a nonprofit organization dedicated to saving farmland for a productive future. Prior to joining American Farmland Trust, Smith served as Administrator of the U.S. Department of Agriculture's Economic Research Service (ERS), which provides high-quality, objective, peer-reviewed research. Dr. Smith has served on several United Nations Expert Panels and chaired the Organization for Economic Cooperation and Development's Joint Working Party on Agriculture and Environment. Her work has been published in books and scholarly journals throughout her career. She is a fellow of the Agricultural and Applied Economics Association and a recipient of that association's Quality in Communications Award. While working at ERS, she was also awarded the Presidential Rank Award for Meritorious Executives in 2001. Dr. Smith earned a B.S. with an emphasis in the Biological Sciences and M.S. and Ph.D. degrees in Agricultural and Resource Economics from the University of Maryland.

Dr. John Soteres, Chair, Herbicide Resistance Action Committee
Dr. Soteres is the Scientific Affairs Global Weed Resistance Management Lead at Monsanto Company, St. Louis, Missouri, and current Chairman of the Global Herbicide Resistance Action Committee. Within Monsanto, his responsibilities include the development and implementation of strategies and stewardship programs for managing herbicide resistance globally. He is also responsible for external collaborations with key academics to further the science relative to the causes of resistance and elucidation of best practices to manage resistance. Dr. Soteres received his B.S. in Biology from the University of Alabama in 1975, an M.S. in Agronomy (Soil Microbiology/Weed Science) from Auburn University in 1978, and a Ph.D. in Agronomy (Weed Science) from Oklahoma State University in 1981. He joined Monsanto in 1981, starting his career as a field Product Development Representative and progressing through a variety of technical management roles during his 30+ year career in the agchemical/agbiotech industry.

Dr. Paul Thompson, W. K. Kellogg Chair in Agricultural, Food and Community Ethics, Michigan State University
Dr. Thompson holds the W. K. Kellogg Chair in Agricultural, Food and Community Ethics at Michigan State University in East Lansing, Michigan. He formerly held positions in philosophy at Texas A&M University and Purdue University. His research has centered on ethical and philosophical questions associated with agriculture and food, especially concerning the guidance and development of agricultural technoscience. This research focus has led him to undertake a series of projects on the application of recombinant DNA techniques to agricultural crops and food animals. Dr. Thompson published the first book-length philosophical treatment of agricultural biotechnology in 1997 and has traveled the world speaking on the subject, delivering invited addresses in Egypt, Thailand, Taiwan,

Mexico, Israel, and Jamaica as well as a number of European countries. In addition to philosophical outlets, his work on biotechnology has appeared in technical journals including *Plant Physiology*, *The Journal of Animal Science*, *Bioscience*, and *Cahiers d'Economie et Sociologie Rurales*. He serves on the United States National Research Council's Agricultural Biotechnology Advisory Council and on the Science and Industry Advisory Committee for Genome Canada. Dr. Thompson's new work focuses on nanotechnology in the agri-food system. In addition to his biotechnology research, Dr. Thompson has published extensively on the environmental and social significance of agriculture. His 1992 book (with four coauthors) on U.S. agricultural policy, *Sacred Cows and Hot Potatoes*, was used as a textbook for U.S. Congressional agriculture staff and won the American Agricultural Economics Association Award for Excellence in Communication. He also has published a number of volumes and papers on the philosophical and cultural significance of farming, notably *The Spirit of the Soil: Agriculture and Environmental Ethics* (1995) and *The Agrarian Roots of Pragmatism* (2000). Dr. Thompson completed his Ph.D. studies on the Philosophy of Technology at the State University of New York at Stony Brook under the guidance of Don Ihde. He is married, has two grown children, and enjoys nature walks as well as playing the guitar.

Dr. Michael Walsh, Research Associate Professor, University of Western Australia
Dr. Walsh is a senior member of the Australian Herbicide Resistance Initiative, where his research role is focused on the development and evaluation of alternate weed control techniques. He has a B.Sc. from the University of Western Australia, an M.Sc. from LaTrobe University in Melbourne, and a Ph.D. from the University of Wyoming. Dr. Walsh has two decades of experience in the management of herbicide-resistant weed populations. Over this period, Dr. Walsh has driven the research and development of harvest weed-seed control systems. Currently he is leading the research on the development of the Harrington Seed Destructor. Dr. Walsh grew up on a dryland cropping farm, and his early experience as a research agronomist with the Victorian state department of agriculture has developed in him a strong focus on applied research aimed at overcoming production constraints.

Appendix D

Herbicide Classifications and Mechanisms of Action

Table D-1 contains the herbicide classifications and mechanisms of actions for herbicides discussed in the proceedings. It is based on Appendix A of the National Research Council report *The Impact of Genetically Engineered Crops on Farm Sustainability in the United States* (2010). Readers can find more information on herbicides, herbicide classifications, and mechanisms of action in that appendix and on the websites of the Weed Science Society of America (www.wssa.net) and the Herbicide Resistance Action Committee (www.hracglobal.com).

TABLE D-1 Selected Herbicide Classifications and Mechanisms of Action

Herbicide Classification	**Abbreviation or Herbicide Example**	**Mechanism of Action**
Acetyl COA carboxylase inhibitors	ACCase inhibitors (e.g., fluazifop)	Inhibitor of acetyl coenzyme-A carboxylase, a pivotal enzyme in plant fatty acid biosynthesis.
Acetolactate synthase inhibitors	ALS inhibitors (e.g., sulfonylurea and chlorimon)	Inhibition of the acetolactate synthase enzyme, resulting in cessation of the biosynthesis of essential branched chain amino acids (leucine, valine, and isoleucine).
Enolpyruvyl shikimate-3-phosphate (EPSP) synthase inhibitor	Glyphosate	Inhibits the EPSP synthase, which leads to depletion of essential aromatic amino acids (tryptophan, tyrosine, and phenylalanine).
Hydroxyphenylpyruvate dioxygenase inhibitors	HPPD inhibitors (e.g., mesotrione)	Inhibition of hydroxyphenylpyruvate dioxygenase, an enzyme involved in the synthesis of plastoquinone and tocopherol (vitamin E).
Photosynthesis II inhibitors	Symmetric and asymmetric triazines (e.g., atrazine)	Inhibit photosynthesis by binding with a specific protein in the photosystem II complex.

Protoporphyrinogen oxidase inhibitors	PPO inhibitors (e.g., lactofen)	Inhibits protoporphyrinogen oxidase, which is in the chlorophyll synthesis pathway. The PPO inhibition starts a reaction in the cell that ultimately causes the destruction of cell membranes. The leaking cell membranes rapidly dry and disintegrate.
Synthetic auxins	Plant growth regulators (e.g., dicamba and 2,4-dichlorophenoxyacetic acid)	Mimics a plant growth regulator. The specific mode of action is not well defined; however, these herbicides mimic endogenous auxin (IAA) and appear to negatively affect cell wall plasticity and nucleic acid metabolism.