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Investigating the Human Dimension of Weed Management: New Tools of the Trade

Doug Doohan, Robyn Wilson, Elizabeth Canales, and Jason Parker*

The human dimension of weed management is most evident when farmers make decisions contrary to science-based recommendations. Why do farmers resist adopting practices that will delay herbicide resistance, or seem to ignore new weed species or biotypes until it is too late? Weed scientists for the most part have ignored such questions or considered them beyond their domain and expertise, continuing to focus instead on fundamental weed science and technology. Recent pressing concerns about widespread failure of herbicide-based weed management and acceptability of emerging technologies necessitates a closer look at farmer decision making and the role of weed scientists in that process. Here we present a circular risk-analysis framework characterized by regular interaction with and input from farmers to inform both research and on-farm risk-management decisions. The framework utilizes mental models to probe the deeply held beliefs of farmers regarding weeds and weed management. A mental model is a complex, often hidden web of perceptions and attitudes that govern how we understand and respond to the world. One's mental model may limit ability to develop new insights and adopt new ways of management, and is best assessed through structured, open-ended interviews that enable the investigator to exhaust the subjects inherent to a particular risk. Our assessment of farmer mental models demonstrated the fundamental attribution error whereby farmers attributed problems with weed management primarily to factors outside of their control, such as uncontrolled weed growth on neighboring properties and environmental factors. Farmers also identified specific processes that contribute to weed problems that were not identified by experts; specifically, the importance of floods and faulty herbicide applications in the spread of weeds. Conventional farmers expressed an overwhelming preference for controlling weeds with herbicides, a preference that was reinforced by their extreme dislike for weeds. These preferences reflect a typical inverse relationship between perceived risk and benefit, where an activity or entity we perceive as beneficial is by default perceived as low risk. This preference diminishes the ability of farmers to appreciate the risks associated with overreliance on herbicides. Likewise, conventional farmers saw great risk and little benefit in preventive measures for weed control. We expect that thorough two-way communication and a deeper understanding of farmer belief systems will facilitate the development of audience-specific outreach programs with an enhanced probability of affecting better weed management decisions.

Key words: Mental models, mental models of weed management, innovation diffusion, organic farmers, conventional farmers.

When scientists warn of global warming, many intelligent people recall a recent severe winter leading them to question the validity of the scientists' claim. Excessive use of jargon and discussion of data are factors that hamper communication and contribute to this common misunderstanding, as is also the case with technical communications between agricultural scientists and farmers. However, an equally important oversight of both climate and agricultural scientists is the failure to frame the discussion in terms of the life experience of the recipient. According to Davis and Olson (1985), data do not become information until ''placed in the context of particular decisions.'' A reliable measure that a message has value to the recipient is when it becomes the basis for a change in behavior. The challenge of effective communication then is related to the general inclination of all humans to judge new ideas within the context of their environment and worldview.

Indeed, the negative reaction of farmers to issues of environment and resource management importance is frequent and usually puzzling to scientists. Two examples of significance to weed scientists are the failure of most farmers to adopt practices aggressively to prevent selection of herbicide-resistant biotypes, and the tendency to overlook new weeds until too late. It is in such examples that we begin to see that our science is about more than biology and ecological interactions and has a compelling human dimension (Luschei et al. 2009). Apple of Peru (*Nicandra physalodes* L.) dispersal throughout two Ohio counties is one example of disparity between academic interest in a phenomenon and that of the farmers most directly affected. Data indicated that an initial infestation localized to a 4-ha field in the 1970s had by 2004 spread to more than 1,000 ha of surrounding fields. Even after intensive weed control enormous populations persisted in a small number of fields, the farm owners did not consider the weed to merit special attention. This incongruence in perception and attitude about the apple of Peru invasion was the crucible around which social, biological, and environmental scientists coalesced in 2006 to form The Ohio State University Agricultural Risk Analysis Program (http://riskanalysis.osu.edu/index.html). It was clear that a ''better understanding of the factors that influence consumers' and farmers' awareness and perceptions of agricultural risks'' was needed.

Innovation Diffusion Theory and Practice

Innovation diffusion is the foundation of agricultural extension programs and marketing campaigns. Everett Rogers and his colleagues first described the theory 50 yr ago after studying how farmers adopt new practices (Rogers 2003). Diffusion of successful innovations follows a sigmoid function in which exponential growth in adoption follows a lag period of slow growth, and in turn is followed by a period of slow or zero growth when the innovation has saturated the consumer

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* First, third, and fourth authors: Professor, Visiting Scholar, and Post Doctoral Associate, Department of Horticulture & Crop Science, The Ohio State University, Wooster, OH 44691; second author: Assistant Professor, School of Environment & Natural Resources, The Ohio State University, Columbus, OH 44210. Current address of third author: Department of Agricultural Economics, Kansas State University, Manhattan, KS 66506. Corresponding author's E-mail: Doohan.1@osu.edu

base. Some innovations are not successfully diffused and adoption never gets beyond the lag phase. Rogers further described diffusion in terms of a normal distribution consisting of a minority of innovators and early adopters, a majority who adopt the innovation deliberately after careful observation and study, and a small minority who never adopt the innovation and are referred to as laggards.

Innovations are new technologies. Almost all technologies consist of a *hardware* component, for instance, a new cultivation implement, and a *software* component, the information base that underlies the implement's development and intended use (Rogers 2003). However, many innovations consist primarily of information. Integrated weed management (IWM) is a predominantly software innovation and as such requires extensive agroecosystem knowledge and application. Complex, system-based ''soft'' technologies are much more difficult to diffuse than predominantly hardware-based technologies (Padel 2001; Rogers 2003).

Diffusion of Weed Management Innovations

By the mid-1990s the U.S. herbicide business was worth an estimated $12 billion (H. Guscar, personal communication). Market penetration of many herbicide-based weed management innovations is remarkable when studied against the backdrop of common innovations such as cell phones. Cell phone technology was approved by the Federal Communications Commission in 1982, and had a market penetration in the United States of 89% in 2007 (http://www.creditcards.com/credit-card-news/credit-score-cell-phone-contract-deposit-1264.php). In comparison, Roundup Ready soybeans, introduced in 1996, were seeded to 91% of the 31.4 million hectares of soybean planted in 2009 (National Agricultural Statistics Service [NAAS] 2009). Understanding why herbicides have been so readily and thoroughly adopted whereas innovations to mitigate their undesirable environmental and biological impacts have been much more difficult to diffuse should be of interest to weed scientists.

Even though innovation diffusion is the underlying principle behind extension programs (Rogers 2003) most weed scientists have not received training in the subject or in the psychology of how humans make decisions. Unintentional patronizing attitudes of researchers and extension educators towards farmers, and assumptions about the factors that influence a farmer's decisions may further impede communication (Vanclay 1992). Extension programs rarely take into account the established learning style of many farmers; specifically, a strong preference for learning by doing, and through farmer-to-farmer networks (Eckert and Bell 2006; Padel 2001). Nowak and Cabot (2004) and Hammond et al. (2006) found that outreach programs that did not consider the values, beliefs, and on-farm decision-making needs of farmers were likely to fail.

Development of IWM was motivated by a desire to provide farmers with systematic approaches to reduce the reliance upon herbicides and their detrimental side effects (Swanton and Weise 1991) including the selection of herbicide-resistant (HR) biotypes (Poweles et al. 1997). As more and more biotypes with resistance to glyphosate and other herbicides are reported, the need to conserve herbicide efficacy has resounded. Why farmers have been slower to adopt IWM in comparison to integrated management of insect and disease pests is poorly understood (Czapar et al. 1995; Hammond et al. 2006). Explanations include market incentives that encourage farmers to rely primarily on herbicides (Llewellyn et al. 2002; Owen 1998), overwhelming complexity of IWM systems (Sanyal et al. 2008), and the essential academic orientation of most IWM research (Moss 2008). Gunsolus and Buhler (1999) found that farmers' perception of the costs required to implement bioeconomic models exceeded the benefit expected from their use. Jones and Monjardino (2006) reported that a focus on short-term gain was a disincentive to implementing IWM. Llewellyn and Allen (2006) found that farmers believed occurrence of resistance on their farm was inevitable, thus resources spent on prevention would be lost. Farmers also prefer to spend resources on weed control activities with certain and immediate benefits rather than prevention of problems that might never develop (Finnoff et al. 2006). These findings correspond well with health-care industry research where it was found that preventive tactics were particularly hard to diffuse because consumers could not ascertain benefits in the short term (Rogers 2003).

The most logical explanation for poor adoption of IWM is that farmers have considered the evidence and made a rational choice, or more specifically a choice that they perceive as maximizing the benefit-to-cost relationship. Farmers need to be able to predict the probable result of practices used to control weeds with reasonable confidence (Moss 2008). Because they generally perceive herbicides as the most predictable control, their choice of an herbicide option over an IWM strategy is rational from that perspective. However, one's experiences, particular knowledge, resources, and decision-making capacity limit rationality. Simon (1990) referred to this as ''bounded rationality,'' describing how experts and novices alike use a series of ''approximate methods'' to make decisions given limited time, resources, and cognitive capacity.

Mental Models: The Theory and the Application

A mental model is a web of beliefs that affects how one defines a problem, gathers and processes information, assesses risks and benefits, and makes decisions (Morgan et al. 2002). Mental models research is known for its ability to yield rich and high-quality data on the complex thinking of a small sample of individuals, often on the order of 20 to 30 (Morgan et al. 1992). Mental models can help identify the reasoning that may limit someone to a familiar pattern of action in complex risk-management decisions. The methodology has been used to determine what people know, and more importantly, what they need to know about issues like global warming (Bostrom et al. 1994), radon in homes (Bostrom et al. 1992), wildland fire (Zaksek and Arvai 2004), food safety (Fischhoff and Downs 1997), and using nuclear energy sources in space missions (Maharik and Fischhoff 1993). Mental models are an ideal foundation for designing risk communications but have not been widely used in agriculture, despite a need to design, strategically, critical communications that will result in improved agricultural management (Llewellyn et al. 2005).

Analysis of farmer mental models can identify how different groups of farmers think about and respond to outreach addressing various strategies and specific tactics. The process begins with the development of an expert-centered technical model, followed by an audience-centered mental model elicited through open-ended interviews (Morgan et al. 2002). The expert model provides the framework from which the audience-centered interview protocol is derived, and serves as the analytical framework to reveal and characterize differences between expert and audience thinking. Data collection ends with a larger confirmatory survey assessment of the target audience informed by the in-depth insights provided by the initial interviews. The survey results inform the preparation and targeting of audience-specific educational programs and evaluation and refinement of those messages.

The overriding purpose in our research was to establish a baseline for how farmers make decisions about weed management. We hypothesized that farmer beliefs, attitudes, and perceptions influence adoption of IWM practices, and also that farmers possessed indigenous knowledge about weeds. The comprehensive expert model for weed management was based on interviews with 12 university and government scientists (Wilson et al. 2008). Sources of introductions, reasons for spread, and negative and positive impacts of weeds and management strategies were discussed. One hundred eighty-six individual concepts were identified and mapped into 30 subcontent areas nested within the five major discussion themes. This original expert model was later augmented to account for organic production through discussions with four more scientists with expertise in organic systems. The farmer model was based on discussions with 30 conventional and 14 organic farmers, interviewed, respectively, in 2007 and 2008. Interviews were approximately 1 h in duration and the protocol consisted of a series of primary and secondary influence questions derived from the major and subcontent areas of the expert model. A primary influence question was posed to begin discussion of each major content area, for example: How are new weeds introduced to a location? This was followed by a series of secondary influence questions, each reflecting a subcontent area, such as: How might humans introduce a new weed to a location? This series of embedded questions enabled the farmer to exhaust his or her mental model fully while allowing the investigator to distinguish between concepts that were of primary importance and those that reflected secondary beliefs. At the end of each interview the subject was asked to identify his or her preferred management techniques concluded each interview.

Methods of analysis are fully described in Wilson et al. (2008). Briefly, data from farmer interviews were coded into the major and subcontent areas of the expert model. Following this initial qualitative coding, a numeric code was assigned to differentiate between primary and secondary responses, and data were analyzed by nonparametric statistics and graphing the frequency of response. Conventional farmers added 26 new concepts to the 186 identified by weed scientists (Figure 1). Organic farmers added eight more.

Insights into the Human Dimension of Weed Management

Although the conceptual models of scientists and farmers largely overlapped, they varied in the number of individual concepts and in the relative importance of primary and subcontent areas. Weed management was the most important principal content area for all three groups, but scientists identified with diverse and IWM, whereas conventional farmers mostly favored timely and diverse use of herbicides. Scientists predominantly identified societal factors that contributed to weed introduction (e.g., vehicle traffic, exotic plant introductions) whereas farmers were most likely to identify environmental factors such as wind, wildlife, and water. Scientists and farmers alike identified environmental, societal, and agricultural benefits and services provided by weeds, but many farmers failed to recognize any benefits.

Considering first how weeds are introduced, farmers identified natural forces, agricultural practices, and nonagricultural human activities as important. However, within these categories important distinctions between the notions held by scientists, conventional farmers, and organic farmers were apparent. Most significant were the implications of those concepts unique to the farmer, specifically, a role for flooding, and poorly managed neighboring lands (Table 1). That 70 and 50% of conventional and organic farmers, respectively, identified flooding as an important force contributing to introduction of weeds should give pause to the weed science community, amongst whom not a single expert mentioned the concept.

Approximately 25% of conventional farmers and 64% of organic farmers attributed weed problems to the behavior of others (poorly managed and vacant neighboring lands) and natural elements (weather, wildlife, and plant characteristics) outside their control, while overlooking the role of their own actions, such as overdependence on herbicides. Here we see the farmers expressing a well-documented tendency of humans to overattribute factors beyond one's control as causative, and underestimating the impact of those factors one does control. This is known as actor–observer bias (Andrews 2001) and was detected frequently in our research.

Agreement between conventional and organic farmers regarding sources and routes of introduction was high. Conventional farmers were more likely to attribute cause to wildlife, to trade and transport in agricultural products, and to human activities such as plant introductions and landscaping. Thirty-three percent of conventional farmers identified intensive herbicide use as a factor leading to new weed problems. High percentages of both farm groups pointed to contaminated agricultural products and equipment as important sources and routes of introduction.

Organic farmers (29%) were much less likely than conventional farmers (77%) to mention the role of seed dormancy in the spread of weeds (Table 1). Perhaps organic farmers are more tolerant of weeds, and may focus less on weed-specific mechanisms of dispersal that lead to uncontrolled outbreaks. However, this attitude more likely reflects inferior knowledge and appreciation of the importance of weed biology. Canales et al. (2008) reported that organic farmers were also less likely to mention the roles of fecundity, plant architecture, and seed-dispersal mechanisms. Previous work by Wszelaki and Doohan (2003) found that organic farmers were largely ignorant of weed taxonomy and identification skills. Conventional farmers are required to attend annual pesticide applicator training in which biology and identification of weeds are regularly discussed. There is no such requirement of organic farmers, which may explain why weed biology was less salient. Sixty percent of conventional farmers reported that faulty herbicide applications were important in the spread of weeds. Both groups recognized a role played by propagule-contaminated equipment, as they did for introductions. However, conventional farmers were

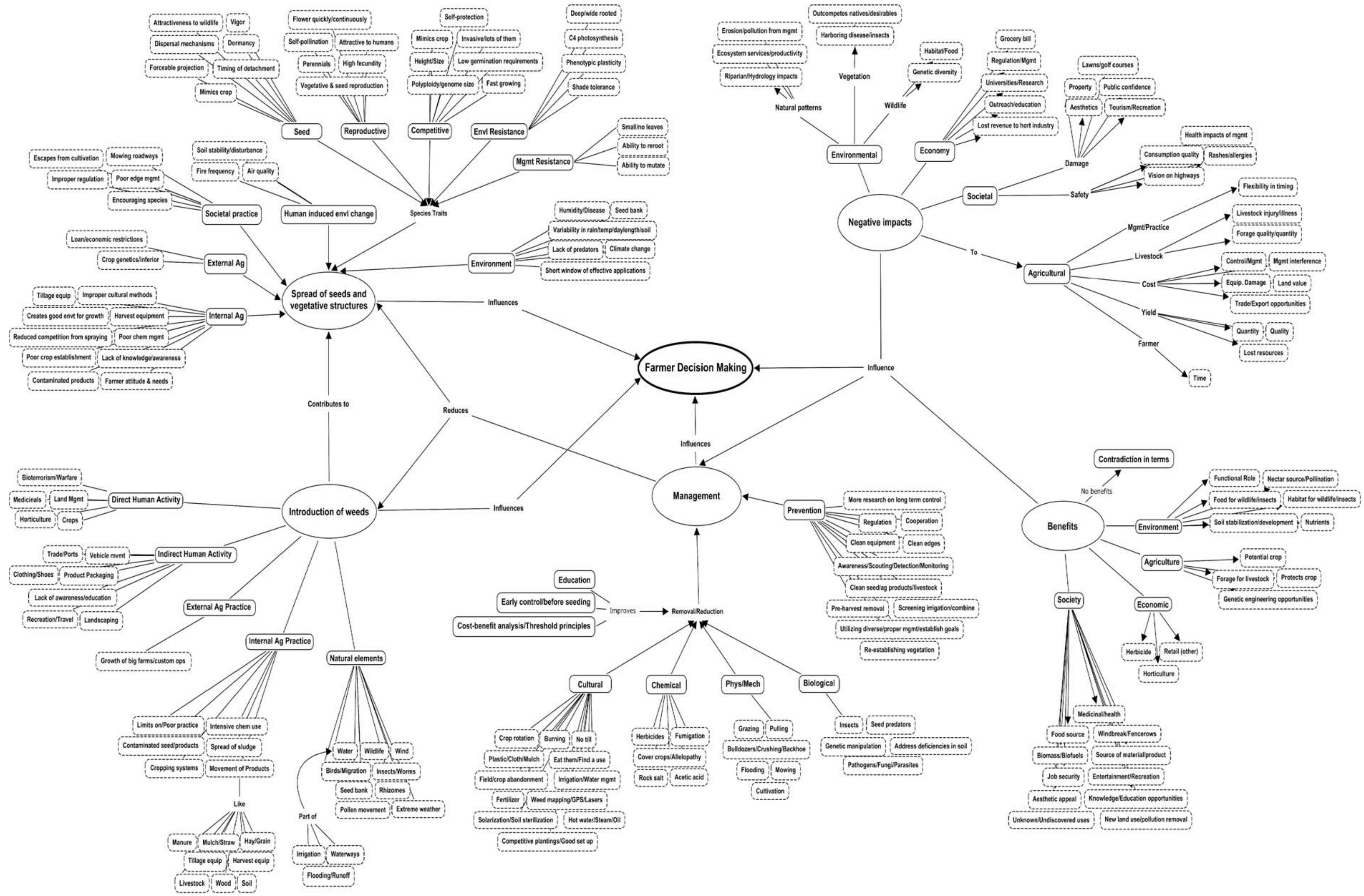

Figure 1. The comprehensive technical model developed with input from weed scientists (from Wilson et al. 2008). Major content areas are depicted by oval nodes, subcontent areas by solid rectangular nodes, and individual concepts by dashed rectangular nodes.

Table 1. Conventional and organic farmer perceptions regarding introduction and spread of weeds, negative impacts and benefits of weeds, management methods, and preferred methods of management.

	Concepts about weeds and weed management				
Introduction	Spread	Negative impacts	Benefits	Management options	Management preferences[a]
% Agreement (amongst conventional farmers/*amongst organic farmers*)					
Wind (97/*86*)	Seed dormancy (77/*29*)	Effects on crops (87/*79*)	Medicinal, health (60/*21*)	Herbicides (100)	Timely, diverse herbicide applications (57)
Wildlife (87/*21*)	Faulty herbicide applications (60)	Cost of production (67)	Soil stabilization (57/*64*)	Cultivation (97/*100*)	Diverse, integrated tools (37)
Flooding[b] (70/*50*)	Equipment (33/*93*)	Human health (83)	Habitat (33/*36*)	Hoeing (*36*)	Clean agricultural products (30)
Contaminated products/ equipment (75/*93*)	Vacant/unmanaged neighboring lands (27/*64*)	Mental stress and reputation (*36*)	Aesthetics (27/*21*)	Hand weeding (47/*21*)	Scouting, early detection (33)
Trade (45)		**Negative genetic material** (27)	Nutrient cycling (*23*)	Rotation (53/*93*)	**Incorrect use of herbicides** (47)
Intensive herbicide use (33)			**Channels for incorporation of organic materials** (*7*)	Competitive plantings (43/*86*)	
Human activities (30)				Improving soil (10/*50*)	
Poorly managed neighboring lands (23/*64*)				Diverse and proper management (80)	
				Prevention impossible (20)	

[a] Only conventional farmers were asked to identify their management preferences.
[b] Bolding denotes concepts not identified in the expert technical model.

more likely to acknowledge equipment as a route of introduction to the farm than as a mechanism of spread across the farm, pointing again to that basic tendency of looking for explanations beyond one's own realm of responsibility.

Farmers uniformly reported the negative impact of weeds on crops; whereas, conventional farmers alone made reference to the impact of weeds on the cost of crop production, and impacts on human health. Expenditures for herbicides may explain why 67% of conventional farmers identified cost of production; however, it is not clear why most of them identified impacts on human health, whereas organic farmers did not recognize this at all. Thirty-six percent of organic farmers reported that weeds created mental stress and damaged farmers' reputation, a concept that was not reported by conventional farmers. This may be related to the greater difficulty in achieving excellent weed control in an organic crop. Eight conventional farmers (27%) reported a concept summarized as contribution of ''negative genetic material'' that had not been identified in the expert model.

With only a few exceptions, conventional and organic farmers mentioned similar benefits of weeds; however, percent agreement varied from concept to concept. Conventional farmers were more likely to acknowledge a contribution to human health. Both groups recognized that weeds play an important role in stabilizing agricultural soils, and provide other environmental services. Twenty three percent of organic farmers identified a specific beneficial role played by weeds in nutrient cycling, and one individual (7%) mentioned the unique concept that weed roots created channels for incorporation of organic materials.

Management strategies most often mentioned involved chemical, physical, and preventive methods. Every farmer in the conventional group identified herbicides. Cultivation was mentioned by 97 and 100% of conventional and organic farmers, respectively. Most conventional farmers (80%) mentioned ideas that were summarized as ''diverse and proper management.'' This was coded as a preventive strategy because it was thought to be an effective approach to mitigate development of herbicide resistant biotypes. Cultural methods were generally not mentioned unless the researcher prompted the interviewee about them, and of those, only crop rotation was mentioned by more than 50%. This was in contrast to organic farmers, who largely (93%) mentioned crop rotation, as well as other cultural methods, including the use of competitive plantings (86%) and improving the soil (50%). Twenty percent of conventional farmers offered the unique concept that prevention was impossible. This notion was undergirded by a conviction that introduction and spread of weeds by wind, wildlife, and water was inevitable.

Conventional farmers were also asked about their preferred methods of weed management. Fifty-seven percent thought that timely and diverse herbicide applications were the best overall approach. Diverse and integrated tools, such as integration of herbicides with physical, cultural, and preventive techniques were cited by only 37%. Even though 80% had previously indicated diverse and proper management as a strategy, this datum indicates the belief was not frequently played out in practice, or was perhaps largely mentioned in regards to diverse and proper herbicide use. Only 30% mentioned the preventive technique of using clean agricultural products, and 33% mentioned scouting and early detection. The later concept is particularly alarming, in that it suggests oversight of many farmers regarding the value of early detection and control. A factor that may have contributed to this is the widespread use of glyphosate-resistant crops. Many soybean farmers in Ohio routinely wait as long as possible before applying glyphosate in order to maximize weed emergence. When asked about the worst possible approach to management, 47% reported the incorrect use of herbicides. This concept seems similar to that of faulty herbicide applications mentioned by 60% of the farmers under the content area of spread, and may correspond to a belief of many farmers that poor herbicide application techniques contribute to development of glyphosate resistance (Johnson and Gibson 2006).

Informing Weed Management Research and Extension Agendas

The mental models approach identified underlying motivational and cognitive processes reflected in the beliefs, attitudes, and perceptions of the participants. Farmers tended to explain the occurrence of weeds and their spread in terms of elements outside of their control: wind, water, wildlife, specific plant characteristics, and the behavior of others. When they did refer to phenomena that occurred on their own farm they usually failed to mention their own role, for instance, in keeping field edges clean. Likewise, they were aware that dirty equipment and contaminated agricultural products introduced and spread weeds but they did not mention their role in keeping the equipment clean or ensuring that they purchased clean products.

Farmers' preferences also reflect a focus on control and not prevention. Twenty percent of the conventional farmers believed that preventing weeds was impossible. The logical outcome of such thinking is that preventive activities are pointless. This belief may be the underlying reason many farmers fail to embrace prevention within their model of IWM even after communication by experts. Llewellyn et al. (2002, 2006) reported similar perceptions amongst groups of Australian farmers facing herbicide resistance. Previous research found that prevention is often perceived as risky and the efficacy uncertain; therefore, risk-averse individuals tend to shy away from taking preventive action (Finnoff et al. 2006; Leung et al. 2002). Research on farmers' risk attitudes found they were willing to give up some potential benefit in exchange for reduced uncertainty in action (Bar-Shira et al. 1997). Outreach modeled on previous failed approaches is unlikely to succeed in diffusing the preventive innovation. Therefore, researchers and extension educators should focus on developing more reason-based approaches, such as relevant case studies that illustrate the cost effectiveness of prevention in the short term.

How farmers explained weed-related events and associated behaviors is consistent with findings from the judgment and decision making literature (Kelley and Michela 1980; Nisbett and Borgida 1975). When individuals observe the actions of others they tend to overattribute their behavior to dispositional factors (i.e., factors within their control) and underestimate the influence of situational factors (i.e., those outside their control). The opposite occurs when individuals explain their own behavior; they tend to overattribute their own behavior or circumstances to situational factors (Jones and Nisbett 1971). We see this phenomenon, known as actor–observer bias, most clearly in the case of organic farmers, of whom 64% attributed weed introduction and spread to a neighbor's inability to manage, a concept that was not included in the original technical model. Case studies and role-playing are just two examples of teaching tools that might be used to help farmers understand and assume more personal responsibilities (Storrie 2006).

Farmers' fundamental knowledge about weeds varied. Most were keenly aware of environmental and agricultural factors that contribute to introduction and spread of weeds, and they identified the potentially important role of flooding that had been overlooked in the expert model. Sixty percent of conventional farmers drew attention to a perception that incorrect use of herbicides was seriously detrimental to weed management. We believe this may be rooted in indigenous observation of resistance evolution; specifically, polygenic resistance as reported by Neve and Powles (2005) and merits closer examination by multidisciplinary teams. In contrast with weed scientists most farmers disregarded the overwhelming role that human behavior, including that of farmers, plays in introducing and spreading weeds. Education that helps farmers to better appreciate the contribution of humans relative to environmental phenomena should elicit an increased appreciation for the practicality of prevention. Teaching weed biology to organic farmers using illustrations that are relevant to their system is an opportunity for specific, targeted outreach. Twenty-seven percent of conventional farmers mentioned weeds as a source of negative genetic material suggesting that extension presentations on gene flow were heard but often misinterpreted. This finding illustrates the importance of strategically framing outreach in language and illustrations that is transparent and relevant to the intended audience.

Farmers perceive weeds as having many negative impacts while having few benefits. Just as they perceive high risk associated with weeds, and as a result low benefit, the reverse phenomenon is true for herbicides. This inverse relationship between risk and benefit is common in risk judgments (Alhakami and Slovic 1994; Fischhoff et al. 1978). Encouraging adoption of IWM will continue to be a challenge as long as current perceptions persist, because IWM implies to the farmer that weed control will be imperfect—that weeds will proliferate, crop yield and quality will be lower, and weed control in future crops will be complicated. Aversion to imperfect weed control is compounded by the farmer's desire to maximize crop yield and financial returns in the short term, minimize the complexity of crop management, and maintain the farm's appearance to neighbors. Consistent with the literature, herbicides are perceived as providing great benefit, and as a result are perceived as low risk (Czapar et al. 1995, 1997; Hammond et al. 2006). As a result, farmers are unlikely to perceive readily any risks associated with their use, including the development of herbicide resistance.

Such perspectives are completely rational based on the mental model of the farmers interviewed in this research. Simon (1990) argued that rationality is bounded by the computational limits of the human brain, requiring application of mental shortcuts known as approximating procedures to address complex problems. Weed management is one of many complex problems faced by farmers and requires the use of approximating procedures to deal with difficult trade-offs between minimizing risk and maximizing benefit, or maximizing short- versus long-term productivity. For example, one such procedure may be the tendency to discount long-term risks (development of resistance) in order to justify a focus on minimizing short-term risks (competition from weeds) (Strotz 1956). Bounded rationality leads to solutions perceived as ''good enough'' because of the inability to address every competing decision-relevant objective adequately. This relates directly to the complexity of weed management and the observation of many that the ecological complexity of IWM is nearly overwhelming to scientists (Sanyal et al. 2008). It is not surprising, given the evidence from judgment and decision-making research, and the complexity of IWM, that farmers use approximating procedures that inevitably and repeatedly lead to the conclusion to use herbicides. We believe it again goes, almost without saying, that relying upon the same tired methods to diffuse IWM will not lead to greater adoption.

Addressing the conundrum of IWM diffusion requires creative outreach by weed scientists that recognizes the mental model through which farmers are making their decisions and capitalizes upon teachable moments. Recent examples of teachable moments in weed management that capitalize on farmer learning styles have been reported in the literature. These include Great Plains dry-land farmers who discovered that diverse rotations including forages and lentils increased profit and reduced weed problems (Anderson 2008), and Canadian-prairie grain farmers who used mode-of-action label information to inform herbicide selection for resistance management (Beckie et al. 2008) and also recognized that the high seeding rates recommended as part of IWM resulted in higher yields under drought than standard seeding rates (Blackshaw et al. 2008). It is these types of lessons that may lead up to a ''tipping point,'' or the threshold that is reached just before a behavioral shift occurs, or a new direction is taken in society. Strategically designed outreach that is targeted towards the information needs of farmers, and designed to reduce an overreliance on heuristics or shortcuts in decision making, will enable weed scientists to engage farmers in these teachable moments.

As mentioned previously, mental models research provides in-depth knowledge of how a representative sample of individuals thinks about and perceives their world. The research reported here supports the need for extension to target to the specific educational needs of key groups. Organic farmers need more intensive and readily available information on weed biology. As such, it should be carefully framed within the context of their decision-making needs and perceptions of weeds in order to be maximally relevant. One size does not fit all. Conventional farmers would benefit from a focus on the environmental services provided by weeds to mitigate the viewpoint that any growth is highly negative. This in turn may encourage less reliance on herbicides and more exploration of diverse strategies that will help minimize development of resistance. Efforts to communicate the cost-effective nature of prevention as opposed to control may help to minimize the perceived risk and uncertainties associated with these techniques, and again encourage greater preventive efforts.

The findings reported here were based on initial qualitative research, and must be followed up by surveys that quantify the strength of the beliefs, perceptions, and attitudes uncovered. Recently we administered a survey that was based on the mental model of the conventional farmers reported herein to 2000 farmers in Ohio and Indiana. Those data are currently being analyzed and will be the subject of a future report. Meanwhile, we have obtained funding to extend our initial mental model of organic farmers in Ohio to other organic farming groups in the United States and in Europe.

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Literature Cited

Alhakami, A. S. and P. Slovic. 1994. A psychological study of the inverse relationship between perceived risk and perceived benefit. Risk Anal. 14:1085–1096.

Anderson, R. L. 2008. Diversity and no-till: keys for pest management in the US Great Plains. Weed Sci. 56:141–145.

Andrews, P. W. 2001. The psychology of social chess and the evolution of attribution mechanisms: explaining the fundamental attribution error. Evol. Hum. Behav. 22:11–29.

Bar-Shira, Z., R. Just, and D. Zilberman. 1997. Estimation of farmers' risk attitude: an econometric approach. Agric. Econ. 17:211–221.

Beckie, H. J., J. Y. Leeson, A. G. Thomas, C. A. Brenzil, L. M. Hall, G. Holzgang, C. Lozinski, and S. Shirriff. 2008. Weed resistance monitoring in the Canadian prairies. Weed Technol. 22:530–543.

Blackshaw, R. E., N. K. Harker, J. T. O'Donovan, H. J. Beckie, and E. J. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian prairies. Weed Sci. 56:146–150.

Bostrom, A., B. Fischhoff, and M. G. Morgan. 1992. Characterizing mental models of hazardous processes: a methodology and an application to radon. J. Soc. Issues 48:85–100.

Bostrom, A., M. G. Morgan, B. Fischhoff, and D. Read. 1994. What do people know about global climate change? 1. Mental models. Risk Anal. 14:959–970.

Canales, E., J. Parker, R. Wilson, M. Tucker, and D. Doohan. 2008. Knowledge, perception and attitudes of organic farmers about weed management. Proc. North Cent. Weed Sci. Soc. Abstract 138.

Czapar, G. F., M. P. Curry, and M. E. Gray. 1995. Survey of integrated pest management practices in central Illinois. J. Prod. Agric. 8:483–486.

Czapar, G. F., M. P. Curry, and L. M. Wax. 1997. Grower acceptance of economic thresholds for weed management in Illinois. Weed Technol. 11:828–831.

Davis, G. B. and M. H. Olson. 1985. Management Information Systems: Conceptual Foundations, Structure, and Development, 2nd ed. New York: McGraw Hill.

Eckert, E. and A. Bell. 2006. Continuity and change: themes of mental model development among small-scale farmers. J. Ext. [Online] 44.

Finnoff, D., J. F. Shogren, B. Leung, and D. Lodge. 2006. Take a risk: preferring prevention over control of biological invaders. Ecol. Econ. 62:216–222.

Fischhoff, B. and J. Downs. 1997. Accentuate the relevant. Psychol. Sci. 8:154–158.

Fischhoff, B., P. Slovic, S. Lichtenstein, S. Reid, and B. Coombs. 1978. How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits. Policy Sci. 9:127–152.

Gunsolus, J. L. and D. D. Buhler. 1999. A risk management perspective on integrated weed management. Pages 225–238 *in* D. Buhler, ed. Expanding the Context of Weed Management. New York: Haworth Press.

Hammond, C. L., E. C. Luschei, C. M. Boerboom, and P. J. Nowak. 2006. Adoption of integrated pest management tactics by Wisconsin farmers. Weed Technol. 20:756–767.

Johnson, W. G. and K. D. Gibson. 2006. Glyphosate-resistant weeds and resistance management strategies: an Indiana grower perspective. Weed Technol. 20:768–772.

Jones, E. E. and R. E. Nisbett. 1971. The actor and the observer: divergent perceptions of the causes of behavior. Pages 79–94 *in* E. E. Jones, et al., eds. Attribution: Perceiving the Causes of Behavior. Morristown, NJ: General Learning Press.

Jones, R. and M. Monjardino. 2006. The economic benefits of adopting integrated weed management. Pages 1–10 *in* T. McGillion and A. Storrie, eds. Integrated Weed Management in Australian Cropping Systems—A Training Resource for Farm Advisors. Adelaide, Australia: CRC for Australian Weed Management.

Kelley, H. H. and J. L. Michela. 1980. Attribution theory and research. Annu. Rev. Psychol. 31:457–501.

Leung, B., D. Lodge, D. Finnoff, J. F. Shogren, M. A. Lewis, and G. Lamberti. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. Proc. R. Soc. Bio. Sci. 269:2407–2413.

Llewellyn, R. S. and D. M. Allen. 2006. Expected mobility of herbicide resistance via weed seeds and pollen in a Western Australian cropping region. Crop Prod. 25:520–526.

Llewellyn, R. S., R. K. Lindner, D. J. Pannell, and S. B. Powles. 2002. Resistance and the herbicide resource: perceptions of Western Australian grain growers. Crop Prot. 21:1067–1075.

Llewellyn, R. S., D. J. Pannell, R. K. Lindner, and S. B. Powles. 2005. Targeting key perceptions when planning and evaluating extension. Aust. J. Exp. Agric. 45:1627–1633.

Luschei, E. C., C. M. Hammond, C. M. Boerboom, and P. J. Nowak. 2009. Convenience sample of on-farm research cooperators representative of Wisconsin farmers. Weed Technol. 23:300–307.

Maharik, M. and B. Fischhoff. 1993. Risk knowledge and risk attitudes regarding nuclear energy sources in space. Risk Anal. 13:345–353.

Morgan, M. G., B. Fischhoff, A. Bostrom, and C. J. Atman. 2002. Risk Communication: A Mental Models Approach. Cambridge, UK: Cambridge University Press.

Morgan, M. G., B. Fischhoff, A. Bostrom, L. Lave, and C. J. Atman. 1992. Communicating risk to the public. Environ. Sci. Technol. 11:2048–2056.

Moss, S. R. 2008. Weed research: is it delivering what it should? Weed Res. 48:389–393.

[NAAS] National Agricultural Statistics Service. 2009. U.S. Crop Acreage Down Slightly in 2009, but Corn and Soybean Acres Up. http://www.nass.usda.gov/Newsroom/2009/06_30_2009.asp. Accessed: December 8, 2009.

Neve, P. and S. B. Powles. 2005. Recurrent selection with reduced herbicide rates results in the rapid evolution of herbicide resistance in *Lolium rigidum*. Theor. Appl. Genet. 110:1154–1166.

Nisbett, R. E. and E. Borgida. 1975. Attribution and the psychology of prediction. J. Pers. Soc. Psychol. 32:932–943.

Nowak, P. J. and P. E. Cabot. 2004. The human dimension of resource management programs. J. Soil Water Conserv. 59:128–135.

Owen, M.D.K. 1998. Producer attitudes and weed management Pages 43–59 *in* J. L. Hatfield et al., eds. Integrated Weed Management. Chelsea, MI: Ann Arbor.

Padel, S. 2001. Conversion to organic farming: a typical example of the diffusion of an innovation? Sociol. Ruralis 41(1):40–61.

Poweles, S. B., C. Preston, I. B. Bryan, and A. R. Jutsum. 1997. Herbicide resistance: impact and management. Pages 57–93 *in* D. L. Sparks, ed. Advances in Agronomy. Vol. 58. San Diego, CA: Academic.

Rogers, E. M. 2003. Diffusion of Innovations. 5th ed. New York: Free Press.

Sanyal, D., P. C. Bhowmik, R. L. Anderson, and A. Shrestha. 2008. Revisiting the perspective and progress of integrated weed management. Weed Sci. 56:161–167.

Simon, H. A. 1990. Invariants in human behavior. Annu. Rev. Psychol. 41:1–19.

Storrie, A. 2006. Case studies. Pages 211–248 *in* T. McGillion and A. Storrie, eds. Integrated Weed Management in Australian Cropping Systems—A Training Resource for Farm Advisors. Adelaide, Australia: CRC for Australian Weed Management.

Strotz, R. H. 1956. Myopia and inconsistency in dynamic utility maximization. Rev. Econ. Stud. 23:165–180.

Swanton, C. J. and S. F. Weise. 1991. Integrated weed management: the rationale and approach. Weed Technol. 5:657–663.

Vanclay, F. 1992. Barriers to adoption: a general overview of the issues. Rural Sociol. 2:10–12.

Wilson, R. S., M. A. Tucker, N. Hooker, J. LeJeune, and D. Doohan. 2008. Perceptions and beliefs about weed management: perspectives of Ohio grain and produce farmers. Weed Technol. 22:339–350.

Wszelaki, A. and D. Doohan. 2003. Comparing weed communities in organic and conventional vegetable farms across Ohio. Proceedings of the OFFER Horticulture Workshop. 24th Annual OEFFA Conference, March 8–9, 2003, Johnstown, OH.

Zaksek, M. and J. L. Arvai. 2004. Toward improved communication about wildland fire: mental models research to identify information needs for natural resource management. Risk Anal. 24:1503–1514.

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