

Community-Based Approaches to Herbicide-Resistant Weed Management: Lessons from Science and Practice

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When herbicide-resistant weeds are highly mobile across farms, delaying resistance becomes a common-pool resource (CPR) problem. In such situations, it is in the collective long-term interest of farmers to conserve an herbicide's usefulness. Yet, each farmer has an individual short-run incentive to use the herbicide without considering effects on resistance. This study considers the potential for community-based (CB) approaches to address problems of herbicide-resistant weeds. Here, growers actively participate in designing, financing, and implementing programs, usually in collaboration with industry, government, and universities. CB approaches have certain advantages over top-down regulatory or subsidy-based approaches. Scholars and practitioners have developed effective governance mechanisms for many CPRs that could aid in developing effective resistance management programs. Successful CB management programs for insect pest eradication and areawide invasive weed control offer additional lessons about the potential and challenges of such efforts. Lessons from these examples can inform the design and implementation of successful, voluntary programs for herbicide-resistance management. Key research, education, and outreach priorities to help implement successful CB programs are identified at the close.

Key words: Areawide, community-based, common-pool resources, herbicide resistance.

Herbicide-resistant (HR) weeds are not a new problem. Episodes of resistance date back to the 1950s with 2, 4-D, and have continued periodically, such as for the triazine herbicides in the 1970s. As of 2015, there has been confirmation of 244 weed species that are resistant to one or more herbicides (Heap 2015). However, the widespread adoption of HR crops (especially glyphosate-resistant corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), soybeans [*Glycine max* (L.) Merr.], sugar beets (*Beta vulgaris* L.), and canola (*Brassica napus* L.) led to dramatic reductions in the diversity of weed control tactics used (Frisvold and Reeves 2014; Norsworthy et al. 2012). This in turn created enormous selection pressure for several weeds to develop resistance (NRC 2010). The reduced diversity in weed-control tactics over so many cropping systems and hectares also means that the geographic and economic scope of resistance problems have become comparably vast. Further, the likelihood of a “silver bullet” solution from a new herbicide discovery appears nil, according to industry sources (Duke 2012).

In response, the search for cost-effective approaches to control HR weeds has taken on new urgency. Scientific and practitioner task forces have produced best management practice (BMP) guides to help growers and their public and private advisers address resistance development on their lands (Burgos et al. 2006; HRAC 2015; Norsworthy et al. 2012). Despite this, HR weed problems continue to spread across cropping systems throughout North America, affecting more and more farmers. Thus far, offering BMP recommendations alone has not changed this trajectory. Now, interdisciplinary groups of scientists are arguing that greater integration of the human and social dimensions of the problem with biophysical aspects is key to creating more effective control strategies (Ervin and Jussaume 2014; NRC 2012; Shaw et al. 2011).

The seminal work of Miranowski and Carlson (1986) highlighted the critical role of pest mobility in designing appropriate policy responses to manage resistance. Early research on managing pest resistance concluded that mobility was a problem with insect pests, but not weeds (Carlson and Wetzstein 1993; Clark and Carlson 1990; Gould 1995; Pannell and Zilberman 2001). A growing body of evidence, however, indicates that weed mobility is more significant and widespread than previously thought (Michael et al. 2010; Wilson et al. 2008). If herbicide-resistance traits are mobile across farms, the susceptibility of those weeds to herbicides is a resource shared by all operators in the community.

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It is in the collective interest of farmers to delay resistance and to conserve the usefulness of an herbicide as a weed management tool. Yet, steps taken by individual farmers in the short run to conserve the usefulness of an herbicide (such as using alternative weed control tactics) can be costly. Delaying resistance becomes a “common-pool” problem—each farmer has an individual incentive to use the herbicide in the short run without considering effects on resistance. Just as every farmer pumping groundwater knows that overdrafting can deplete an aquifer in the long run, each still has an individual incentive to pump in the short run. As such, individual farmers might not manage resistance because they are not assured their neighbors will match their actions. This situation sets up the well-recognized “tragedy of the commons” where the susceptible weed gene pool will be exhausted without some form of intervention (Hardin 1968; Webster and Sosnoskie 2010).

The common-pool nature of weed susceptibility means that managing resistance is not just an agronomic problem, but a social one as well. A fundamental question then becomes, “What type of social organizations can effectively manage common-pool resources?” Early scholarship on the tragedy of the commons focused on the need for public action of some sort, but further study documented success of privately-led, community-based (CB) initiatives (Ostrom, 1990).

This paper analyzes the scientific and policy ramifications of CB approaches to managing herbicide resistance. First, we review the state of evidence on the mobility of herbicide-resistant weeds and explain the causes of common-pool resource failure. Then, we discuss different approaches to common-pool resource management and their advantages and limitations, ranging from government regulation to private grower and commodity-association efforts. Third, we discuss the design principles that have emerged from case studies in the United States and around the world. In the fourth section, we examine community-based programs for insect pest and invasive weed management. Lessons from these programs can inform the design and implementation of effective and socially acceptable applications to herbicide resistance. We conclude by summarizing the potential for community-based resistance management and the research and education implications for weed science and collaborating disciplines.

Sizing up the Evidence on Weed Mobility

Earlier writings by economists did not view common-pool issues as problematic for managing herbicide resistance (Carlson and Wetzstein 1993; Clark and Carlson 1990; Pannell and Zilberman 2001). Llewellyn et al. (2001) noted, “it is generally assumed that growers ‘raise and own’ their weed problem as a private property resource.” Clark and Carlson (1990) developed a theoretical model and statistical tests of whether growers managed different pesticides as open-access resources or private property. For the United States, they found support for the joint hypothesis of resistance build-up and open-access problems for insecticides, but not for herbicides. Clark and Carlson’s (1990) analysis covered 1950 to 1984, however. It appears to have captured behavior just before the period of sharp increase in cases of herbicide resistance (Heap 2015). From an entomologist’s perspective, Gould (1995) suggested that common-pool problems would be less of an issue for weeds than insects because the “tighter population structure” of the former, and that “herbicide abuse on one farm will have less of a direct effect on other farms” (p. 834), although he conceded that more studies on this issue were needed.

Although resistant weeds might be less mobile relative to insects, this does not mean that mobility is not a problem in an absolute sense. Resistant weed seed can be transported great distances via movement of farm equipment (Diggle and Neve 2001; McCanny and Cavers 1988). Seed also can be transported via shipments of hay (Schmidt and Pannell 1996). This mechanism can be more pronounced during drought when hay is often transported over greater distances (Diggle and Neve 2001). Palmer amaranth seed can spread via irrigation and other water flows, with the movement of animals, and through plowing, mowing, harvesting and spreading compost, manure, or cotton gin trash (Barber et al. 2014; Norsworthy et al. 2009). Weed scientists have also documented cases of resistant alleles transferred to susceptible populations through pollen movement, seed, or other propagules, in some cases at great distances (Beckie et al. 2013, 2015; Borger et al. 2007; Busi et al. 2008; Dauer et al. 2006, 2007; Lu et al. 2007; Rieger et al. 2002; Shields et al. 2006; Sosnoskie et al. 2007, 2012; Watrud et al. 2004).

In response, weed scientists have begun to acknowledge common-pool problems and call for more collective regional responses, considering participation of neighboring farms (Beckie et al.

2015; Shaner and Beckie 2014). Similarly, social scientists are increasingly acknowledging common-pool problems in herbicide-resistance management (Ervin and Jussaume 2014; Frisvold and Reeves 2010; Llewellyn and Pannell 2009; Marsh et al. 2006). Whether or not a given weed species is especially mobile is an empirical question, but common-pool problems might exist simply if growers believe that weeds are mobile. There is evidence that growers believe managing resistant weeds is largely beyond their control and dependent on neighbor actions (Llewellyn and Allen 2006; Wilson et al. 2008). Such beliefs might be sufficient to discourage growers from proactively managing resistance.

Why Community-Based Approaches?

Common-pool resources (CPR) pose special management challenges, primarily because resource users have open or unregulated access to the resource. Individual users have no assurance that other users will match their good stewardship efforts. These uncoordinated actions can exhaust the resource stock over time. In the case of herbicide resistance, the weed gene pool that is susceptible to the herbicide(s) in question is the resource stock of concern. That stock is influenced by the herbicide applications of all users in the community. Without some type of program that controls how much farmers apply, the selection pressure can produce significant weed resistance and higher costs for current and future producers in the community.

Hardin's 1968 essay in *Science* gave widespread recognition to the CPR issue with the "tragedy of the commons" language. After this introduction, the literature and policy discussions focused on the need for some type of public (government) regulatory scheme to avoid degradation of the common resource. Nonetheless, one can envision at least three stereotypical approaches to control access to the resource: (1) top-down government regulation; (2) public or private payment schemes to discourage practices that diminish the resource stock; and (3) bottom-up, community-based programs. Brief discussions of these three approaches show why the last could be attractive for dealing with herbicide resistance.

Many environmental programs use top-down regulations authorized by law as a basis for controlling access to common-property resources. The Clean Air and Clean Water Acts are prime examples. The regulations typically prescribe ac-

ceptable production practices (practice-based) or emission discharge (performance-based) limits. They are enforced by monitoring compliance and by assessing monetary and sometimes even criminal penalties for noncompliance. This legalistic approach can be socially preferred when depleting a resource (e.g., air or water quality) threatens public health or when authorities want to avoid the risk of catastrophic damages (e.g., hazardous spills). In such cases, the regulatory costs imposed on the parties causing the resource degradation can pale in comparison to the substantial benefits. For example, U.S. air pollution regulations were estimated to deliver an estimated 30 to 1 benefit-cost ratio for 1990 to 2020 (US EPA 2011). However, their stringency can turn into one of the chief criticisms of top-down regulations, (i.e., their inflexibility stymies innovation and keeps compliance costs high). Studies have found that the command-and-control approach taken in the Clean Air Act and Clean Water Act has dramatically improved U.S. air and water quality, but that these improvements could have been achieved at much lower cost if programs had been designed more efficiently (Field and Field [2012] provide examples and references). Granting the regulated entities some flexibility in how to meet the practice requirements or pollution limits can significantly lower compliance costs, as sulfur dioxide pollution-permit trading schemes have demonstrated (Field and Field 2012).

In general, farmer production practices have not been directly regulated through command-and-control regulations. This is because for such regulations to be feasible, the pollution sources must be clearly identified and monitored. This applies, for example to dairies and feedlots. It is not practical and extremely costly, however, to monitor the on-farm production practices of the more than two million U.S. farms. This would be particularly difficult for on-farm resistance management (Frisvold and Reeves 2014). For example, it would be difficult to monitor and enforce a requirement that farmers control weed escapes, start with a clean field, control weeds when small, clean equipment, or other resistance-management practices. Farm practices could be regulated indirectly, through pesticide regulations. For example, certain pesticides might be approved for use only in alternating years. However, pesticide cancellations or use restrictions could be quite blunt and expensive policy instruments. Uniform restrictions that do not account for the differences across regions and crops can be particularly costly (Sunding 1996).

A more common approach to altering farm-level production practices is to provide farmers with public or private payments to adopt more environmentally benign practices. This payments-based approach has been more common in agriculture because costs of monitoring on-farm practices is prohibitively expensive and because of agriculture's significant political power in state and federal policy-making (Ervin 2013). Since the 1980s, farm legislation has introduced a variety of programs to provide farmers with government payments to conserve resources, with a mixed record of success (Ervin 2013). These include programs such as the Conservation Reserve Program (CRP), the Wetlands Reserve Program (WRP), the Environmental Quality Incentives Program (EQIP), and the Conservation Stewardship Program (CSP) (Claassen and Ribaudo 2007). Under these programs, payments are based on adoption of particular practices or technologies, not on actual environmental performance (such as soil erosion or fertilizer runoff), because the latter is very difficult to monitor over space and time at the farm level.

One problem of payments for practices rather than performance is that practice adoption might not have desired environmental outcomes in many settings. Payment schemes can also have limited ability to actually change behavior, termed *additionality* (Claassen et al. 2014; Segerson 2013). Payments are additional only if they induce farmers to adopt practices that they would not undertake without the payments. If producers receive payments for practices that they have already adopted or for practices that it would be profitable to adopt anyway, these payments do not lead to any additional resource conservation. Here, the payments simply become income transfers to farmers. This has been the case with a number of U.S. agricultural conservation programs (Ervin 2013). Similarly, payment levels might be too low for some farmers, so that they provide insufficient incentives to conserve resources. Achieving *additionality* and therefore cost effectiveness, requires significant monitoring and data collection to assure the payments result in the desired changes in behavior (Segerson 2013). Thus, payment schemes can have many of the same problems of command-and-control regulations. Adoption of uniform practices, either by mandate or encouraged by subsidies, can be highly inefficient if production systems are highly diverse, as they are in agriculture. Further, both can have high monitoring and enforcement costs, given the sheer number and diversity of producers. A final

issue with using public payments is the costs of such inefficiencies are borne by taxpayers rather than by those regulated.

Some payment-based programs have already been implemented by industry to improve resistance management. Monsanto has begun offering price rebates to growers who purchase residual herbicides to be used in conjunction with glyphosate. These subsidies apply to herbicides with modes of action that differ from glyphosate, and even apply to some herbicides sold by competing companies (Volkman 2010). Whether and how much *additionality* these rebates have achieved awaits formal evaluation. Another question is the ultimate cost of payments large enough to encourage widespread residual use. Mitchell (2011) estimated that if only 10% of farmers using Roundup Ready[®] cotton and soybeans received maximum rebate levels, total costs would have been nearly \$39 million for 2011 alone.

The third approach of community-based efforts stands in contrast to top-down regulation or incentive schemes that appear frequently in the tragedy of the commons literature. This strand of scholarship and practice emerged from scientists and practitioners who observed that open-access resource situations do not always lead to uncoordinated and competitive exhaustion of the common resource. They set about to analyze what situations and conditions were most likely to spawn cost-effective and sustainable community-based initiatives (e.g., Ostrom 1990).

In CB programs, resource users are actively involved in the design, financing, and implementation of programs. Usually, there is collaboration with industry, government, and universities. The role of government here is distinctly different from that of the top-down, command-and-control or payment-based approaches. It is often as a facilitator and provider of scientific knowledge and complementary investments. Implementation and compliance still require significant design and monitoring effort and cost, as well as a clear delineation of the relevant community of stakeholders. Although resource users might benefit from government technical and financial assistance, they often must also provide their own additional funds through internal support schemes.

The development of community-based approaches for resistance management rests primarily on three rationales. First, the resource appropriators, or farm operators, have the most intimate knowledge of the local natural resource and social conditions. Second, as such, they are more likely to develop

resistance-management practices that fit their local agronomic, economic, and social circumstances. Third, resource users have a direct stake in creating institutions that are fair and effective because they need assurance that their neighbors will reciprocate their good stewardship actions. This last argument implies that the resource users have an interest in conducting monitoring and applying appropriate penalties when some operators do not comply with locally prescribed resistance-management practices. That inclination will likely lead to more reasonable monitoring and enforcement costs than with top-down approaches.

Despite these persuasive rationales, not all community-based approaches succeed. Elinor Ostrom, corecipient of the 2009 Nobel Prize in Economics, synthesized the findings of diverse studies around the globe to identify 10 factors that significantly affect the likelihood that resource users will self-organize for collective action (Ostrom 2009). The factors can be used to evaluate the feasibility of CB approaches to resistance management.

1. Size of the resource system. Very large systems are unlikely to self-organize because of the high cost of defining boundaries, monitoring and assembling ecological knowledge. Small systems might not produce enough valuable services to induce such action. For these reasons, moderate sized systems are most conducive to self-organization.

2. Productivity of resource system. There is an inverted U-shaped relationship between resource productivity and self-organization. If a resource is either abundant or already exhausted, users perceive few incentives to pursue collective action for conservation. Some scarcity (value) is necessary to induce their efforts.

3. Predictability of system dynamics. Resource system dynamics need to be understood well enough so that the effects of management actions on the resource can be accurately predicted. Unpredictability can deter users from self-organization because of a lack of assurance of effective group actions.

4. Resource unit mobility. Self-organization is less likely for highly mobile resources, such as wildlife or water in an unregulated river, that range over great distances. As argued above, herbicide resistance often exhibits spatial mobility. This means resistance-management organizations would need to

cover a large enough area to encompass the major factors contributing to resistance.

5. Number of users. Larger groups of resource users have higher costs to organize, but also can assemble labor and other resources to cover administration, monitoring, and other costs. The effect of group size on self-organization depends on the particular socioecological system and is indeterminate a priori.

6. Leadership. When some resource users have entrepreneurial skills and enjoy the respect of others, the likelihood of collective action increases. For example, the presence of college graduates and local elders in the resource system can exert positive effects.

7. Norms/social capital. Users of resource systems who share moral and ethical standards of group behavior, including the norms of reciprocity and trust, will have lower transaction costs in reaching agreement and be more likely to self-organize and carry out effective monitoring.

8. Knowledge of the socioecological system. When users share common knowledge of the resource system—its vulnerabilities to excessive use, how their actions affect each other, and the rules used in other systems—they will perceive lower costs of organizing. If this knowledge is lacking and the resource system regenerates slowly, the risk of excessive degradation rises.

9. Importance of the resource to users. If the resource in question plays a significant role in the welfare of the users, they are more likely to perceive that the gains from collective action to conserve the resource will outweigh the costs of organizing and maintaining.

10. Collective choice (governance) rules. If users have full authority and autonomy to take collective action to develop and enforce rules, they face lower transaction costs of organizing and less expense in implementing controls to defend the resource from exploitation by external parties.

Design Principles for Community-Based Approaches

Ostrom collaborated with scientists both in the United States and from around the world during her career to synthesize eight design principles for stable local CPR institutions (Ostrom 1990). Understanding the content of each principle is critical to building successful community-based programs. We build on the introductory discussion

of the principles related to herbicide-resistance management (HRM) in Ervin and Jussaume (2014).

1. Establish clearly defined boundaries. Implementing this principle requires the definition of two types of boundaries: identifying the geographic area that must be governed by the CB program, and identifying the parties within the boundary who must be engaged in the CPR effort (Cox et al. 2010). For application to HRM, the geographic region over which the selected herbicide and weed resistance travels must be delineated in approximate terms. In doing so, the population of relevant growers will be assured that all people who can affect the resource have been identified for involvement in the CB effort. This assurance is key to stimulating reciprocity and effective HR stewardship. The boundaries of the region will depend upon the zone of weed pollen and seed mobility in question, and therefore will depend on the state of the science on that specific topic. If the boundaries cannot be identified with acceptable confidence, then sufficient participation and assurance will not be achieved, and the CB approach will be problematic.

2. Develop congruence between the appropriation and provision rules for the common resources that are adapted to local conditions. This principle also has two dimensions: the first is that appropriation and provision rules conform to local social and environmental conditions, and the second that appropriation and provision rules are in alignment (Cox et al. 2010). Following the first capitalizes on the local knowledge and experience of farm operators who understand the biophysical and social intricacies of weed development and mobility in their area. This enables the population of farmers who use the herbicide(s) in question to adapt the CPR institution to the requirements and conditions on the ground. The second dimension involves achieving proportionality between the inputs of labor, material, or money provided by resource users (in this case farmers) and the benefits they receive from participation in the community-based collective action (e.g., the avoidance of extra costs once resistance develops and possibly averting added costs from top-down regulations). In essence, this involves meeting both benefit-cost and fairness tests for the rules.

3. Implement collective-choice arrangements that allow most resource appropriators to participate in the decision-making process. Similar to principle 2,

following this principle would empower most resource users to participate in the CPR decision process and thus take advantage of the local knowledge of the special resource and social conditions. In general, their knowledge and experience provide lower cost information to administer the system of controlling resource access. Some commentators feel the principle is good in concept but in practice can be thwarted by the uneven distribution of local power or external bureaucratic actors who see gains from promoting particular management practices.

4. Conduct effective monitoring by monitors who are part of or accountable to the resource appropriators. This principle has two components: (1) monitors must be appointed by the community-based effort, and (2) monitors must be part of the community and accountable to the full set of appropriators (Cox et al. 2010). Following the principle makes monitoring an integral part of managing the common resource and engages those who have extensive knowledge of the resource situation. This generally leads to lower costs than if an external party (e.g., state or federal agency) monitors. In addition, the monitors should benefit (either by improved resource condition or other rewards) if they perform satisfactorily (i.e., monitoring is incentive-compatible). Finally, the monitoring system performs two key functions, identifying resource appropriators who are not in compliance and collecting information on the common resource condition that can inform the CB activities.

5. Institute a scale of graduated sanctions for resource appropriators who violate community rules. This principle of imposing sanctions on resource appropriators who do not comply with the rules imposed by the CB program is critical to success. Without a credible threat of the sanctions, experience indicates that some portion of the appropriators will not comply (Ostrom et al. 2012). Social cohesion of the group is insufficient. Research on business environmental management has found that the threat of regulatory sanctions is associated with an increased intensity of “voluntary” environmental management (Ervin 2013; Segerson 2013). Hence, if the sanctions for noncompliance with CPR rules to foster improved HRM are visible and significant, a higher level of participation and compliance should ensue. Imposing graduated penalties sends a signal to resource appropriators that larger departures impose proportionately higher costs on other resource users. Although not specified in the

principle, the body responsible for imposing the sanctions can be within the private community-based organization or codified in legislation and administered by a public agency.

6. *Create mechanisms of conflict resolution that are cheap and easily accessible.* Conflicts between appropriators using a common resource are inevitable. Access to cheap and easy conflict resolution procedures at the local level enhances the probability of decentralized solutions to CPR management problems, rather than elevating dispute resolution to higher and more distant bodies. The principle does not specify the form of the conflict-resolution mechanism, except that it is low-cost and easy to access. Some CPR institutions rely on the state and federal court systems (e.g., water sharing arrangements), whereas others have privately administered bodies that adjudicate appeals or charges about noncompliance.

7. *Higher-level authorities recognize self-determination of the community.* To implement effective community-based efforts for managing CPR issues, local and state laws must grant the rights to private nongovernmental organizations to be free from challenge by external parties. This surety is necessary to foster long-term planning and vests the local parties with ownership of the issue. It also conveys tenure security to the resource appropriators, a condition that promotes long-term investment from a longer planning horizon.

8. *For larger common-pool resources, organization in the form of multiple layers of nested (polycentric) enterprises might be required.* When CPR issues are large enough to span multiple jurisdictional boundaries, single local CB initiatives might be insufficient to exercise sufficient control over resource appropriation. This does not mean that local CB efforts would not be part of an effective solution. Rather, other entities at distant points or at higher levels of administration could be required to assure sufficient coordination and effective action to conserve the common-pool resource. The approach in these cases can be thought of as nested or polycentric governance, and the nesting can run either in horizontal or vertical directions. For HR problems, this type of approach might be necessary when weed seed dispersal occurs through climatic, water, or mechanistic (e.g., transport) processes, and requires control across space and perhaps coordination at the state or federal level.

Generalization of principles from diverse cases is always challenging and subject to scrutiny, as any

good scientific investigation should be. Agrawal (2003) has critiqued the synthesis work in that the implied cause-and-effect relationships are not as robust as the principles imply. He argues, for example, that smaller groups do not always form CB programs that are more effective, even though transaction costs likely are lower. Further, increased group heterogeneity does not necessarily impede collaboration. He also notes problems with CB efforts. These include: (1) monitoring and enforcement are still needed and possibly could be costly (institutional capacity and resources to monitor and enforce might be limited); (2) comanagement programs with government entities might give local communities only very limited scope for decision and rule making; (3) locally agreed-upon rules can be essentially nonbinding constraints and amount to too little action; (4) boundaries of resource management problem can be unclear; and (5) identifying noncompliance is difficult (Agrawal 2003). Each of these complications reinforce the importance of designing HRM approaches to fit local socioecological conditions.

Despite these challenges, the design principles have received significant support. In one of the most ambitious studies of CPR management, Cox et al. (2010) assessed the performance of 91 programs to evaluate the statistical support for each of the eight design principles. Their overarching finding was that each of the design principles was well-supported empirically. They recommended, however, that three of the principles (1, 2, and 4) be split into two components as described above to improve analytical power and insight. Although this meta-analysis provides a measure of confidence for using them to inform CB experiments for HRM, we note that careful analysis will be necessary, because previous applications in agriculture have not focused on weed resistance, but insect management and other common-pool resource issues. Indeed, Cox et al (2010) conclude that three main critiques of the principles are valid: (1) they are incomplete; (2) they might not apply to a wide range of cases beyond those used to develop the principles; and (3) the principles abstract from the heterogeneity and messiness of environmentally and socially embedded CPR situations. We turn next to some experiences in agriculture to discern possible lessons for forming effective community-based approaches to HRM.

Lessons from Community-Based Efforts in Agriculture

In this section, we examine four types of community-based efforts to control insects and weeds to consider what lessons they might provide for resistance management. The four are: (1) areawide insect control programs, (2) insect eradication programs, (3) areawide invasive weed control programs, and (4) weed districts and Cooperative Weed Management Areas. In what sense are these programs “community-based?” First, local, private land managers are actively involved in defining the design and geographical scope of these programs, in addition to monitoring and implementing the program. Second, local entities do not just participate in these programs, but have key leadership roles in program implementation and evaluation. Third, successful implementation of these programs often relies on social networks at the community level to affect change. Fourth, even though these programs have (to varying degrees) mandatory requirements and regulatory authority, local farmers, ranchers, or political jurisdictions agreed upon these mandates and regulations beforehand.

These types of programs are not new. Programs to eradicate cotton insect pests—pink bollworm in California and the boll weevil in the U.S. South—were initiated in the late 1960s and early 1970s. Weed districts, local entities authorized through state legislation to impose taxes and land use regulations to control weeds, date back further, at least to the 1930s (Fairchild 1935; Fiege 2005). Why consider such programs? First, they arose specifically to address common-pool resource management problems associated with agricultural pests. Second, they were frequently established in response to resistance to pesticides (Calkins and Faust 2003; Chandler 2003; Hardee and Henneberry 2004). Third, some have been quite successful at achieving their objectives, providing both economic and environmental benefits. Fourth, despite the differences in the contexts and goals of these programs, they share many common structural features and prerequisites for success. These features and prerequisites can guide the design and implementation of successful programs to manage herbicide resistance. Finally, not all programs have been complete successes, and even successful programs had, at times, met with difficulties. One can learn from difficulties as well as successes.

Areawide Programs for Insect Control. There has been a long history of areawide programs to control cotton insect pests. An early Community Management program was initiated in the mid-1970s to control cotton bollworm and tobacco budworm (Hardee and Henneberry 2004). One key program feature was pest scouting with treatment thresholds based on community-wide evaluations rather than field-specific thresholds. Another was treatment of the entire community with chemical or microbial insecticides. By improving pest control, the program increased areawide grower profits by an average of nearly \$46 per hectare (Cochran 1996). In 1989, cotton growers in California’s Imperial Valley implemented a short-season cotton program to control pink bollworm. The program called for mandatory dates for earliest planting, latest date for defoliant application, and latest date for plow-down. The program reduced larvae per boll and insecticide use, while increasing lint yields and quality (Chu et al. 1996). In Arizona, a 1989 to 1995 areawide program relied on adoption of gossypure for mating disruption (Antilla et al. 1996). Larval infestations in cotton bolls fell from 23% in 1989 to < 1% by 1995. Hectares chemically treated to control pink bollworm fell dramatically and costs of pink bollworm control fell from historic highs of more than \$170/ha down to \$70/ha. (Antilla et al. 1996; Frisvold 2009; Henneberry 2007). Growers in southern California and Mexico’s Mexicali Valley implemented similar gossypure-based programs (Staten et al. 1987).

In 1993, as part of an overall Integrated Pest Management (IPM) Initiative, the USDA, Agricultural Research Service (ARS) began developing a formal framework to encourage collaborative areawide, pest control programs (Faust 2008; Faust and Chandler 1998; Hendrichs et al. 2007). USDA provided technical support and financial support to cooperating entities and made direct public investments in project activities. Project implementation was carried in multiple stages. First steps included defining the geographic scope of the project and selecting of initial demonstration sites. Selected projects shared a number of requirements and objectives. They addressed specific barriers to implementing pest control on a needed, regional level. There was extensive collaboration between (multiple) USDA agencies, land-grant universities (including cooperative extension), and local agricultural producers. Projects were also to have formal mechanisms to ensure cross-entity communication and collection of biological, environmental, and

economic baseline data. The impetus for a number of projects was the emergence of pests resistant to pesticides (Calkins and Faust 2003; Chandler 2003).

Projects also shared a number of critical program elements (Calkins and Faust 2003; Keenan and Burgener 2008; Keenan et al. 2007). There was an appreciation of the role of economic and sociological factors in influencing farmer and landowner participation and intensity of effort. Although challenging, the projects recognized the need to demonstrate the economic benefits of areawide and individual participation. Benefits needed to be demonstrated clearly and within a period short enough to encourage adoption. Next, projects made extensive use of remote sensing and geographical information system (GIS) technology to actively and continually monitor program performance. Private and public entities each played key roles in implementation. Farmers and land managers were often those on the ground directly implementing practices. The public sector's role was primarily to provide services that individuals did not have the capacity or incentive to provide to others. These public goods included scientific understanding of the problem, technical support, and coordination services among multiple groups. Public agencies could also provide a broader perspective than individual farmers, ranchers, or producer groups might have. Finally, there was recognition that a specific person was often needed to serve a constant coordinating function. In some cases, this duty fell to areawide cooperative extension personnel. In others, full time coordinators were hired (Calkins and Faust 2003).

Eradication Programs. Pest eradication programs for insects can be thought of as extensions or special cases of areawide control. What makes them different? First, pest eradication is a weakest-link, public-good problem (Caplat et al. 2012; McCoy and Amatya 2005; Perrings et al. 2002). Eradication is a public good because all affected derive benefits from it; individuals have an incentive to “free ride”—to undersupply their own effort. Eradication is a “weakest link” problem because the success of the program depends on the performance of those putting in the least effort. For pest control in general, Knipling (1972) noted: “Uniform suppressive pressure applied against the total population of the pest. . . will achieve greater suppression than a high level of control on most, but not all of the population.” Hendrichs et al. (2007) note further,

“A few free riders or ‘refuseniks’ can negate many positive impacts of AW [areawide] programs.”

For eradication, a high level of effort by only some producers might completely fail. As has been observed with disease eradication, nonparticipation by pockets of individuals with the least capacity or incentive to participate can thwart eradication (Perrings et al. 2002). This means that the adoption and diffusion of eradication measures will not proceed under patterns discussed by Rogers (2003) where diffusion proceeds from early stage innovators to early adopters to later adopters and nonadopters. In the Rogers framework, later adopters witness and learn from the success of earlier innovators, whereas late- or nonadopters do not affect adoption benefits of others. In weakest-link problems, however, there might be few early benefits to observe without widespread participation, so incremental learning is less possible. Further, nonadopters can negatively affect returns to those who attempt to innovate (Rebaudo and Dangles 2011; Thomas, 1999).

Eradication requires something closer to universal participation from all growers. For this reason, pest eradication programs in the United States have instituted mandatory compliance and practice adoption for all growers. For boll weevil and pink bollworm eradication programs, growers have voted for the program in referenda on a state-by-state basis. Adoption of the eradication program required that two-thirds of the growers in the state (or region) approve the program (Bordelon 2005; Dumas and Goodhue 1999; Grefenstette et al. 2009). Once approved, however, all growers in eradication area are subject to the program mandate. Compared to other areawide programs, eradication programs rely more on mandatory requirements and regulatory authority. This regulatory authority, however, is granted by a vote and support of a super-majority of the group and is not imposed top-down. The regulatory authority of the state and federal government here is in the background in a supporting role, to prevent individuals from free riding once an agreement has been reached.

Eradication programs also share a number of key elements. First, they are financed jointly by the federal government, state governments, and by growers themselves (Dumas and Goodhue 1999; Szmedra et al. 1991). Growers are assessed charges either per acre or per unit of output to partially support the program. Because grower groups have “skin in the game,” they have greater incentive to

design and implement cost-effective programs. The USDA has provided technical expertise and financed additional public investments, such as sterile moth releases (Grefenstette et al. 2009; Walters et al. 2009). Cooperative extension staff (in counties and at land grant universities) are also actively involved. A scientific understanding of how the eradication program would work, and an economic understanding of the benefits and costs of the program both short- and long-term are critical. Eradication programs often involve a short-term increase in pesticide use and so can meet with criticism. They have tended, however, to significantly reduce long-term pesticide use. Thus, an understanding of short- and long-term environmental effects is also critical. Continual monitoring and reporting of program activities are also crucial. Successful programs have moved from eradication to “posteradication” phases. In the latter, pest population monitoring, inspections, and prophylactic measures are maintained to prevent reinfestation into areas where the pest has been eradicated are maintained. Thus, although program activities and costs are significantly curtailed in the posteradication phase, the programs have never completely ended.

Growers have not always been convinced of the value of eradication programs, and there are instances of referenda failing on their first attempts (Haney et al. 2009; Myers et al. 1998). Kazmierczak et al. (1996) cite lack of landowner cooperation with producers as an impediment to participation in eradication programs. They also found that providing detailed information did not necessarily encourage participation and that demand for participation was lower in areas where the target pest was less of an immediate problem. In a study of Georgia cotton farmers, Ahouissoussi (1995) found important effects of grower heterogeneity on willingness to participate. Larger-scale, more educated growers were more likely to have already adopted proactive pest control measures. These same growers were less pleased with the Boll Weevil Eradication Program (BWEP) program because they felt there were lower additional gains from group control efforts. Smaller-scale producers favored group control measures if these measures reduced complexity of management decisions.

Estimated benefits of pest eradication programs have been substantial. Long-term economic benefits include higher yields (and gross revenues) and lower pest control costs (Ahouissoussi et al. 1993; Carlson et al. 1989; Duffy et al. 1994; Frisvold 2009; Haney

et al. 2009; Larson et al. 2000). In addition to per-hectare benefits of eradication, hectares planted to cotton can also increase because of eradication (Dumas and Goodhue 1999; Tribble et al. 1999). In addition to economic benefits, there are additional long-term environmental benefits of reduced applications of broad-spectrum insecticides (Bordelon 2005; Frisvold 2009; Haney et al. 2009; Tabashnik et al. 2010).

Areawide Invasive Weed Programs. The USDA Areawide Program also included projects addressing invasive plants. Projects have focused on leafy spurge (*Euphorbia esula* L.), melaleuca [*Melaleuca quinquenervia* (Cav.) Blake], saltcedar (*Tamarix ramosissima* Ledeb.), downy brome (*Bromus tectorum* L.), and medusahead [*Taeniatherum caput-medusae* (L.) Nevski] (Anderson et al. 2003a,b; Carruthers 2003; Hodur et al. 2006; Prosser et al. 2002; Smith and Sheley 2012). These projects have much in common with the insect programs in terms of overall objectives and structures; yet, they also have some important differences. Most are in the western United States where most of the land is managed by federal agencies (Forest Service, Bureau of Land Management, and the National Park Service). The melaleuca project in Florida requires substantial interactions with public land and water agencies. In these cases, public agencies are not just providing technical and financial assistance, but are directly responsible for managing public lands where invasive plants abide. A second, important difference is that there are many sources and sinks for these species besides cropping systems. The types of land uses and land managers can be quite heterogeneous, forming complex “management mosaics” which pose special problems (Epanchin-Niell et al. 2009). With greater subdivisions of land, each land manager considers a smaller share of overall damages, and there is greater potential of reinfestation from neighbors. As land uses and managers become more diverse, managers will be less likely to have shared incentives for control. Further, land controlled by the “weakest links”—those with the least capacity or incentive—can become reinfestation sources to other lands.

Local Weed Management Organizations. Weed districts are local entities usually established under state legislation, with some dating back to the 1930s (Fairchild 1935; Fiege 2005). These districts, in some cases, had legal authority to require landowners to control specified noxious weeds. If the landowner failed to comply, the district could treat

the weeds itself and require the landowner to pay for the treatment (Clawson 1977). County weed programs, which receive annual county funding and operate within the confines of county borders, have regulatory authority to enforce local weed control ordinances. Cooperative Weed Management Areas (CWMAs) are partnerships of federal, state, and local government agencies, tribes, individuals, and other interested groups that manage noxious weeds or invasive plants in a defined area (Midwestern Invasive Plant Network 2011). CWMAs operate within a defined geographic area pertinent to control of particular weeds, but they tend to span administrative boundaries and involve participation of private landowners and local, state, and federal agencies. A main function of CWMAs is coordination of activities across diverse jurisdictional boundaries. Weed Prevention Areas (WPAs) are similar to CWMAs in overall structure. A key difference is that WPAs focus on prevention, whereas CWMAs are often focused on areas where invasive plants have already become problems (Goodwin et al. 2012). A number of groups have provided on-line resources with step-by-step guides for organizing a CWMA or WPA (e.g., Midwestern Invasive Plant Network 2011; Christen et al. 2011). Finally, grassroots weed organizations rely on citizen volunteers who donate time to control weeds, frequently on public land.

Hershendorfer et al. (2007) surveyed 53 such local weed management programs in four southwestern states to assess how program attributes affected program performance. Program performance was measured by the extent of weed control, outreach activities, weed monitoring, and adoption of integrated weed management practices. They found that programs with greater interagency coordination and greater volunteer participation did more monitoring. Programs that relied on private citizen volunteers to carry out weed control treated a significantly smaller proportion of acres. This might be because volunteer groups often rely on digging or hand weeding rather than chemical applications. The former are labor-intensive, meaning fewer acres can be treated. Volunteers might be averse to applying chemicals or simply lack adequate training to make chemical treatments. Hershendorfer et al. (2007) found interesting differences between three program types. The first possessed regulatory authority over landowners and actively enforced regulations. The second type lacked any regulatory authority. Clawson (1977) had noted that completely voluntary groups are less divisive, but “likely

to be least effective when most needed.” The third type possessed regulatory authority (i.e., it could issue official written warning letters or fines), but chose not to do so. Hershendorfer et al.’s results suggest that this third group, the group that had regulatory authority but used a “light hand” to achieve results treated a significantly greater proportion of their infestations than the other two groups. Respondents in the third group noted that they relied on persuasion more than direct regulation because they felt it would be more effective. Groups following more punitive tactics had less success.

The State of Delaware Noxious Weed Program also appears to be following the “light handed” approach. Palmer amaranth and five other weed species are on the state’s noxious weed list. Landowners who do not control noxious weeds can, under law, be fined \$25 per acre (\$100 minimum) (VanGessel and Johnson 2015). In practice, however, fines are a last resort and no fines have been collected in the last 7 yr (T Davis, Delaware Department of Agriculture, personal communication). Instead, staff members of the Delaware Department of Agriculture (DDA) make visits to farms to develop written compliance plans with growers. It is felt that fines are not effective at achieving compliance. Instead, it is most effective for local landowners to see DDA spraying noxious weeds on state lands or roadsides in a timely manner.

The approach taken by these weed management programs appear in contrast to many of the insect programs, especially eradication programs, which have tighter mechanisms for compliance. Other work (as noted above) on CPRs has found graduated sanctions to be a key element in program success. Eradication programs, however, have had documented evidence of success. The metrics for success for the weed control programs to date have been practice-based rather than performance-based.

Implications for Herbicide-Resistance Management Programs. The various programs discussed above address several common themes with direct implications for implementation of community-based programs to manage herbicide-resistant weeds.

1. Requirement for strong scientific basis. This includes both a solid theoretical understanding of biological mechanisms, as well as understanding of how strategies might succeed (or fail) in different agronomic settings. This condition would help meet

the need for predictability of system dynamics to facilitate self-organization efforts (Ostrom 2009). A strong scientific underpinning is essential to receive financial and technical assistance from federal agencies and acceptance by farmers.

2. *Effective communication of scientific principles.*

This requires strong linkages between university and private sector research and extension programs. Pilot studies that apply an incremental approach can help demonstrate program potential to wider areas.

3. *Active involvement of social scientists.* Understanding socioeconomic dimensions are important for understanding the social context of current practices, barriers to adopting new practices, and group dynamics. Economic analysis can aid in demonstrating the potential gains of program implementation beforehand and to estimate the economic benefits of successful, mature programs.

4. *Need for strong leader/coordinator.* In some cases, full-time coordinators were hired. This acknowledges the fact that CB efforts entail significant transactions costs that can be an overwhelming time commitment for most farmers. In some case, this function is partially fulfilled by cooperative extension staff. Even here, however, coordinating CB activities is likely a full-time responsibility if it is to be effective. Having strong leadership has been found as a significant factor in furthering such self-organized efforts (Ostrom 2009).

5. *Need for ongoing monitoring, reporting, and evaluation.* This is important for establishing baselines and monitoring program progress. In some cases, grower groups might already be in place with monitoring and practice requirements. Pest eradication areas are examples. Groups and institutions active in these prior programs could serve as a basis for self-organization around herbicide-resistance management. Certain resistance-management practices are readily observable to outside evaluators and neighboring growers—use of crop rotations and cover crops, for example. We recognize that these land-use practices are only one part of resistance management. However, readily observable land-use practices can be monitored over time and provide neighbors assurance of compliance.

6. *Need to establish clear geographic boundaries.* This requirement, supported by theory and experience, is critical to prevent in-migration of resistant weeds from outside a resistance-management area. Adopting comprehensive boundaries presents certain

challenges, however. First, as geographic scope increases, so does the diversity of agricultural production systems (cropping systems) and producer types (hobby farms vs. commercial operations). Different groups might have different incentives and capacities to manage resistance. Attaining group cooperation might require additional transaction costs and transfer and support mechanisms to encourage adoption. Further, purely commodity-based organizational structures might be insufficiently comprehensive. Within agriculture, cross-commodity approaches, could be necessary because farmers might grow multiple crops simultaneously and in rotations (e.g., corn, soybeans, and cotton) that contribute to resistance in synergistic ways. In addition, different producer groups might not readily see how their weed management decisions affect each other. For example, dairy operations growing silage crops will likely not account for how their behaviors alter weed resistance facing field crop producers. Groups outside agriculture might also need to participate, for example. Weed management along roads, rights of way, and ditch banks requires actions off farmlands and by nonagricultural land managers. Agencies with authority over public lands, such as conservation areas, can affect herbicide resistance by their management of weeds and waterways. The participation of public land managers (especially in the West where much land is publicly managed) will be necessary for comprehensive resistance management. This would include federal agencies (e.g., Forest Service, Bureau of Land Management, and the National Parks Service) as well as state departments of transportation, state parks, and state lands departments.

Results from other programs suggest some challenges CB resistance-management programs can face. Some programs emphasized the importance of simplicity of practices in encouraging adoption. This could be a particular challenge for CB herbicide-resistance programs. Recent trends have been toward (over) simplification of weed management systems and reduced diversity of tactics. Diversified resistance-management programs will likely be more complex and management-intensive. Managing to avoid resistance (as opposed to addressing resistance problems after they arise) also requires proactive management. However, other studies have found that demand for participation in CB programs is relatively low among farmers not currently facing a problem.

The Zero Tolerance program to address herbicide-resistant Palmer amaranth in Arkansas shares a

number of core features associated with successful community-based programs (Barber et al. 2015). First, there has been substantial research conducted to gain understanding of how the development and spread of resistant weeds can be delayed (Jha et al. 2014; Norsworthy et al. 2014). Second, there is an appreciation (based on science and experience) that strong local leaders are required to maintain program focus. Third, there has been emphasis on developing an identity among local grower groups committed to addressing resistance. Growers have established Zero Tolerance zones ranging in size from just a few hectares to more than 8,000 ha. As has been the case with other community-based programs, impetus for the program emerged after the particular problem (in this case, herbicide-resistant Palmer amaranth) had already become acute. The development of proactive community-based programs aimed at prevention in other areas will be a challenge. Resources developed to assist the establishment of Weed Prevention Areas (Christensen et al. 2011; Ransom and Whiteside 2012) can assist in developing programs to prevent herbicide resistance.

Summary and Implications

Recent evidence portrays a striking increase in herbicide resistance, both in terms of the number of weed species that are resistant and the number of states and provinces in North America that are affected (Heap 2015). We argue that when significant weed mobility exists, community-based actions can help lead to sustainable herbicide-resistance management. However, knowing that some form of private or public collective action is required in such circumstances does not make it easy. Progress in preventing herbicide resistance will require experiments that draw on theory and experience from other common-pool resource regimes. Approaches that have succeeded elsewhere will need to be adapted to specific, local socio-ecological situations. We summarize key theoretical insights and experiential lessons that can guide development of constructive approaches and draw implications for research and extension.

Research on the adoption and diffusion of innovations suggest that resistance-management practices will be more widely adopted if they (1) exhibit a clear economic advantage, (2) are not too complex, (3) are adoptable on a limited, trial basis, (4) have rapidly observable benefits, and (5) are consistent with pre-existing farming practices (Rog-

ers 2003; Keenan and Burgener 2008). The degree of weed mobility across weed species and local, socioecological conditions will affect the degree to which these factors that facilitate diffusion are present. Where these facilitating factors are present, CB approaches might not be necessary. Three cases that turn on the degree of mobility can be used to assess the potential usefulness of a CB approach.

In the first case, mobility is not a significant problem. Resistance management becomes an individual farmer problem to solve by comparing the costs of managing resistance over time, e.g., labor and machinery costs of more tillage, with the yield and other benefits of avoiding resistance in future years. The solution is a standard extension approach—give farmers appropriate information so that they can make better long-run decisions. This will still be challenging because many resistance-management practices can entail lower profits in the short run, with less-certain benefits accruing only in the future.

In the second case, mobility might be a factor, but an individual grower still has an incentive to manage resistance no matter what neighbors do. In other words, collective adoption across a broader area might be the best strategy, but individual growers can still benefit from adoption even when their neighbors do not. In terms of game theory, managing resistance on one's own farm is a dominant strategy. This outcome was suggested for corn in a recent analysis by Livingston et al. (2015). Here, the traditional extension approach might be effective. It remains a policy question whether the extra transaction costs of organizing resistance-management programs for community-wide compliance generate sufficient additional collective benefits.

In the third case, mobility is a large enough issue such that managing resistance is a weakest-link public good. In this case, a farmer's benefits from managing resistance can be negated if neighbors do not manage as well. Because the welfare of a farmer is dependent on the actions of all other farmers, the farmer who manages least determines the outcome for the community as a whole. This result was found for soybeans in the analysis of herbicide resistance by Livingston et al. (2015). In this case, many of the facilitators of innovation diffusion (Rogers 2003) will likely be absent.

Our analysis pertains to the two latter cases of herbicide resistance, for which potential net benefits of cooperative behavior exist. Three overarching lessons from the science and experience with CB

efforts can help realize those benefits. A critical early step is to engage all groups in the locality who have a stake in managing herbicide resistance. A meta-analysis of wicked problems involving agriculture and conservation concluded that strengthened stakeholder capacity is a key principle in making progress (Sayer et al. 2013). Stakeholders can extend beyond farmers and their public and private cropping advisers (including input suppliers) to include local government and community organizations and conservation/environmental groups. Such broad engagement takes more time and increases cost over traditional extension approaches. However, the engagement process builds social capital and lower transaction costs to discover a more effective and durable approach. Neutral facilitators and respected local leaders are vital to conducting a constructive stakeholder process. Some extension professionals might require professional training in facilitation if they assume this role. These same professionals in turn likely have experience with the local innovators in farming communities where they work. These local innovators could be crucial to initiating CB programs.

Building the institutional capacity necessary to design and implement a CB program will take time and maintenance. The character of the wicked HR problem requires experimentation and adaptive management to discover an approach that works within the local socioecological system. Critical members for this task include scientists and professionals who understand the productivity and system dynamics of the problem being addressed. Those experts can advise participants about the pros and cons of CB practices and processes but refrain from specific recommendations. This will enable the stakeholders to take ownership of the institutions developed and implemented.

It is critical to engage both natural and social scientists because wicked problems in socioecological systems invariably require both sets of expertise (Ervin and Jussaume 2014). The work of Ostrom and her colleagues on self-organization and CPR management provides a rich body of knowledge that requires interdisciplinary teams to effectively apply. This integrated approach might be easier for private sector organizations because they must focus on problem solving, in contrast to academic professionals who focus on advancing scholarship in their own disciplines.

New scholarship is necessary to apply these lessons to herbicide-resistance problems. As noted above, few CB programs have been established to

directly address herbicide resistance. Therefore, little evidence exists on the factors that determine their success or failure. More research on the processes that influence growers' participation is essential to understand the biophysical, economic, and social challenges and opportunities that shape those outcomes. No single survey will satisfy this need. Findings from local, state, regional, and national surveys are necessary to enrich our understanding of the complex individual and group choice processes. The surveys will require interdisciplinary approaches to unravel the complexities of this coupled human–natural systems challenge. Further, the farmer decision for managing HR via CB approaches needs to be set within the whole farm system, rather than as a separate component.

Although few CB programs have addressed HRM, a large body of knowledge has been assembled on CPR management that can inform such efforts (e.g., Ostrom 2009). In short, we do not have to start from scratch to make progress. To avoid reinventing the wheel, we propose a clearinghouse of information on successful CPR programs that can be used to assemble “how-to” guides to assist private and public groups to chart a productive path to progress on this complex problem. An essential part of that information base will be insights into what approaches were not productive and under what circumstances.

With the new knowledge and understanding of the salient factors influencing farmer's decisions to engage in CB approaches, attention can turn to education and training programs. The success of extension education in furthering the development of U.S. agriculture has been well documented (Huffman and Evenson 2008). The dominant approach used by extension professionals and university researchers working with farmers on crop production issues has been “one-on-one.” Our scientific theory and experiential data suggest that a different skill set and approach will be necessary to effectively apply CB approaches to herbicide-resistance cases involving significant mobility. Increasingly, the literature on innovation diffusion has emphasized community aspects of adoption and the role of social networks (Rogers 2003; Keenan and Burgener 2008). Weed science professionals will need to use their substantive knowledge but also engage professionals in the social and behavioral sciences who have expertise in forming effective group efforts. For example, we suggest access to high-quality facilitation services will be necessary in forming effective CB approaches.

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