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Integrating Social Science into Managing Herbicide-Resistant Weeds and Associated Environmental Impacts

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Controlling herbicide resistance (HR) and its associated environmental risks is impossible without integrating social and economic science with biophysical and technology aspects. Herbicide resistance is a dynamically complex and ill-structured problem involving coupled natural–human systems that defy management approaches based on simple scientific and technology applications. The existence of mobile herbicide resistance and/or herbicide tolerance traits add complexity because susceptibility to the herbicide is a resource open to all farmers, impacting the weed population. Weed scientists have extensively researched the biophysical aspects and grower perceptions of HR. They also recognize that the ‘‘tragedy of the commons’’ can appear when herbicide resistance is mobile across farms. However, the human structures and processes, especially private and public institutions that influence individual and group decisions about HR, have received little analysis. To start filling that gap, we discuss an integrative management approach to sustainable weed control that addresses the social complexity of farm heterogeneity. For example, the need for a private or public collective mechanism becomes apparent to address common-pool resource (CPR) aspects when one farmer's weed control actions influence their neighbors' situations. In such conditions, sole reliance on education, technical assistance, and other incentives aimed at changing individual grower behavior likely will fail to stem the advance of HR. Social science theories can be used to enrich the understanding of human interaction with the biophysical environment and identify key actors and social change processes influencing those interactions in the case of HR. The short-run economic advantages of herbicides such as glyphosate work against social change to address HR, including the development of collective actions when mobile HR conditions exist. We discuss seven design principles that can improve the efficacy and cost of such collective approaches and draw insights from CPR approaches outside of HR.

Nomenclature: Glyphosate.
Key words: Adaptive management, biophysical, common-pool resources, economics, herbicide resistance, interdisciplinary research, social capital, social science.

Herbicide resistance (HR) is not a new phenomenon, starting with episodes in the 1950s (NRC 2012). Nonetheless, the current situation that is highlighted by the surge in the number and pervasiveness of glyphosate-resistant (GR) weeds introduces broader risks than previous instances because of the widespread use of glyphosate as the primary means for controlling weeds in several major crop production systems in the United States (Boerboom and Owen 2007; Vencill et al. 2012). A national scientific assessment of genetically engineered (GE) crops concluded that escalating weed resistance problems pose significant risks to the natural environment (Ervin et al. 2010). Some of the potential negative environmental effects of HR include increased soil erosion, carbon emissions, and water quality degradation. The Ervin et al. report (2010) also emphasized that it is impossible to address these negative environmental effects without also addressing social and economic dimensions of the problem. In other words, an accurate assessment of the long-range sustainability of these cropping systems is impossible to achieve without connecting environmental with social and economic dimensions.

Weed scientists and other scholars have contributed to an extensive literature on the biophysical and management aspects of HR weeds. For example, an early analysis of common-pool resource (CPR) issues compared aspects of insect and weed biology to determine whether resistance management strategies for insects were likely to be helpful in addressing HR (Gould 1995). Interfarm mobility of insects with attendant CPR issues has been a major source of insect resistance. The analysis concludes that differences in the genetic architec-

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ture, mating systems, and population structure of insects and weeds lead to differences in the likely efficacy of certain resistance management strategies. With respect to CPR issues, Gould (1995) advances the hypothesis that if weeds have a stronger population structure than insects, i.e., weeds are less geographically mobile, then individual farm HR management can be effective because it can be easier to get farmers to participate because they don't have to worry about their neighbors' actions. Hence, he recommends theoretical and empirical studies to examine the population structure of weeds. The rapidly increasing number of HR weeds since that analysis was conducted suggests that the population structure (or other mechanisms of mobility) of those weeds have made individual farmer actions less than effective.

Webster and Sosnoskie (2010) analyzed the causes and impacts of losing glyphosate efficacy in Georgia cotton (*Gossypium hirsutum* L.). They trace the major changes in cotton production arising from the introduction of glyphosate-tolerant (GT) cotton cultivars in 1997 and widespread adoption, driven by large economic and other advantages, despite a cost premium. The composition and structure of weed communities in cotton fields were altered due to imposed selection pressures, and the number and seriousness of HR weeds grew, e.g., Benghal dayflower (*Commelina benghalensis* L.) and Palmer amaranth (*Amaranthus palmeri* S. Wats). The authors addressed CPR complications: "Glyphosate susceptibility in the most frequently and troublesome weed species is a common resource that is being rapidly lost in Georgia because of a lack of overall stewardship." (Webster and Sosnowskie 2010) They urge more research to discover new incentive mechanisms to improve herbicide stewardship, a central point of our analysis.

Shaw et al. (2009) analyzed the telephone interview responses of 175 farmers in each of four Corn Belt and two southern states to assess their perceptions of the benefits of utilizing the GR crop trait in corn (*Zea mays* L.), cotton, and soybeans [*Glycine max* (L.) Merr.] and the weed management challenges growers were facing after using the GR trait for at least 4 yr. Growers in Mississippi and North Carolina indicated that they had a strong majority of their croplands in continuous monocropping systems, whereas a majority of respondents in Illinois, Indiana, Iowa, and Nebraska did not. Given the propensity for HR selection pressure to increase under monocropping, the authors concluded that the southern United States, cropping systems were at higher risk of developing HR problems. That geographical pattern has indeed occurred. In a separate analysis of the survey data, Johnson et al. (2009) found that only 30% of farmers thought GR weeds were a serious issue. The findings showed that most farmers did not appreciate the role recurrent herbicide use plays in fostering HR weeds, likely a prerequisite to devising an effective control strategy.

The findings of the three studies illuminate important biophysical and grower management aspects of HR. However, the human (e.g., personal values) and social (e.g., community) networks, influences, and growers' experiences with CPR aspects of HR weeds were not analyzed in any depth. For example, Vencill et al. (2012) present an excellent review of the biophysical and individual grower management aspects of HR weeds, but do not broach interfarm HR weed mobility that cause CPR issues. Our paper aims to start filling the social science knowledge gap to enable more effective management of the natural–human interactions that spread HR weeds.

A plethora of public and private programs to control HR weeds have not slowed the overall spread of HR in the United States (NRC 2012). Furthermore, despite recent laudable attempts to promote a consensus set of technically effective best management practices (BMPs) (Norsworthy et al. 2012), significant progress appears to be wanting.

> Most growers adopt most HR BMPs much of the time, but this has been insufficient to delay resistance … More troublesome, the most effective practices are used least. (G. Frisvold, personal communications)

Moreover, the use of BMPs by individual farmers likely will not effectively control HR weeds when CPR conditions remain. Most current HR management approaches deliver education and technical assistance (E&TA) to growers who can voluntarily use the information. A rich literature shows that this dominant E&TA approach to promote natural resource conservation in agriculture has met with uneven adoption of BMPs due to weak incentives and significant barriers facing many farmers (Ervin 2013). In addition, various educational and incentive programs often fail to take into account the fact that farm-level decision-making takes place within complex social–cultural settings.

The central thesis of this analysis is that developing a sustainable management strategy for

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HR weeds requires the integration of social and economic science with biophysical science and technological innovation. In other words, developing a new "silver bullet" weed control technology will not solve the problem. Indeed, current glyphosate resistance problems have emerged in large part because of an over-reliance on a single, albeit powerful, technology with a single mode of action. Farmers adopted this simplistic approach to weed control with most GE crops because of multiple benefits and lower costs (Ervin et al. 2010). The short-term advantages have been evident in the dramatic rates of adoption of GE HR varieties of cotton, corn, and soybean (USDA ERS 2013). However, GR weeds are eroding those benefits and increasing long-term economic and environmental costs, many of which will be passed on to future generations.

This paper asserts that a departure from a technology-reliant strategy by individual farmers to an integrative management approach that reflects the natural and social complexity of farm heterogeneity is necessary for sustainable weed control. In other words, weed resistance to herbicides is not simply a technological problem that can be remedied, for example, by new herbicide chemistries. Characteristic of such "wicked problems," scientific uncertainty about biophysical, social, and economic interactions that shape HR problems complicates a definitive formulation and clear solution criteria, necessitating adaptive management approaches (Batie 2008). In particular, many of the causes, and possible solutions, to herbicide resistance when weed mobility and CPR issues apply, cannot be understood without an understanding of the influential roles that social and economic factors play. Human decisions within the herbicide development and innovation process led to the creation of a management approach that, because of its simplicity, mimicked a homogenous industrial setting more than a natural one. As noted above, farmer economic decision models explain why the herbicide-tolerant approach has been popular with growers in the short run. However, a deeper analysis of processes in structural, sociological models explain why simplistic, rather than integrative, approaches are less likely to create a system that recognizes the complexity of processes associated with human decision making, as well as the complex interaction between human and ecological conditions. In addition, failure to use institutional economic models for CPR weed cases when a farmer's weed management influences the evolution of HR weeds in neighbors' fields have also contributed to the spread of herbicide resistance.

Clearly, analyses of the social and economic conditions associated with different weed management strategies is needed to understand the causes of the HR problem and develop potential solutions that mitigate environmental risks. Weed scientists need to incorporate an empirical understanding of the heterogeneity of growers' behaviors, values, and capacities, as well as household and community conditions, as part of an interdisciplinary assessment of HR issues and the design of weed management programs. Altering HR BMP-use patterns also requires an appreciation of growers' behaviors in managing CPR in varying biophysical and social situations. Social science gaps in the literature on HR preclude such a comprehensive understanding. The main purpose of our paper is to explicate the interconnection of human behavior and CPR dimensions of HR-associated environmental issues in order that weed scientists can begin to incorporate these insights into their future work. We conclude by highlighting the implications for advancing HR research and management.

Human Drivers of Herbicide Resistance

Our main argument is that the HR problem cannot be mitigated without addressing the human dimensions, including social, economic, political, and cultural aspects. One way to demonstrate the necessity of incorporating a human dimension as part of plans to address the environmental problems associated with herbicide resistance is to highlight how human dimensions contributed to the emergence of this problem. In other words, although herbicide resistance clearly can be explained from an evolutionary and technical perspective, human factors also contributed to the creation of a socio-ecological context from which resistance emerged.

Many approaches can be used to highlight the human dimension in natural resource-related issues. One common approach analyzes how human interaction with the physical environment influences socio-ecological change (Busch and Juska 1997; Coughenour 2003; Morgan et al. 2006). We borrow from this approach in our analysis to highlight some of the key human actors, and some of the key social and economic decisions, that contributed to the evolution of herbicide resistance. This is NOT meant to be an exhaustive analysis of all of the human dimensions of the HR issue, but merely an exercise to underscore that the evolution

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of herbicide resistance is not solely, or perhaps even primarily, a technical issue.

The (weed) scientific explanation for the rapid spread of weed resistance is built upon how weeds have responded to the creation of narrow growing conditions that created an environment wherein resistant weeds had an optimal chance for survival and reproduction. In other words, the widespread use of a technology with a single mode of action increased selection pressure for those weeds that were resistant to that technology and subsequently led to the rapid evolution of herbicide-resistant weed species (Holt 2012). Particularly in corn, soybeans, and cotton production, the widespread use of glyphosate-dominated weed management strategies led to the development of growing conditions that are characterized by their comparative uniformity. A social science perspective would expand on this analysis by understanding the human structures and processes that influence the individual and group decisions about the development and use of this technological approach.

Glyphosate was developed in 1974 by the Monsanto Agricultural Products Company (Duke et al. 2003). Unlike some earlier pesticides, glyphosate was known to break down readily in the soil and was effective on virtually all plant species. This meant that although glyphosate could be used effectively on most weeds, it could not be used in row crops after germination. Consequently, "until 1996, glyphosate use was restricted in agriculture to its 'traditional' use for nonselective burndown of weeds prior to crop seeding or for weed control between established rows of tree, nut, and vine crops." (Duke and Powles 2009) In other words, glyphosate was one tool that was used as part of a set of management practices that agricultural producers used to control weeds.

The ability to transfer genetic information from a bacterium that had resistance to glyphosate into commercial agricultural crops marked a significant change in the use of this herbicide and the management of corn and soybean crop production. Monsanto, which held the patent on glyphosate until 2000, became a leader in transferring glyphosate resistance into these crops. GR soybeans were introduced in 1996 (Dill et al. 2008), with GR corn and cotton being released in 1997 (Duke and Powles 2009). This provided Monsanto with the opportunity to gain dual profits from the sale of glyphosate as well as the seeds that produced the plants that would be resistant to the chemical (Duke and Powles 2009). This development and dissemination of this business strategy was an understandable economic decision made by a very powerful human organization.

Agricultural producers, for their part, were now able to apply glyphosate postemergence (POST). With the introduction of GR crops, glyphosate could be utilized as an in-crop, post, selective herbicide. Because glyphosate was effective on virtually all competitor plants, weed management was simplified. In addition, the use of this strategy helped reduce the use of tillage for weed control, which led to environmental gains in terms of minimizing soil erosion and improving soil health, and to economic gains in terms of reduced labor (Ervin et al. 2010; Norsworthy et al. 2012). These direct benefits to agricultural producers help account for the rapid speed with which so many producers adopted this technological package at the farm level. Within 4 yr, over 50% of all acreage in soybeans (2000) and cotton (2001) in the United States had the glyphosate-resistance trait, although the 50% margin was not achieved in corn until 2007 (Ervin et al. 2010).

These decisions, and those made by other actors in the private and public sectors were understandable human decisions driven by human interests. A major perceived benefit from the viewpoint of the human actors was the further advancement of production systems in soybeans and corn that were, because of their simplicity, easier to manage. In the case of herbicide management, use of herbicides other than glyphosate declined (Bonny 2008; Fernandez-Cornejo et al. 2000) and farmers became increasingly dependent on a single chemical with a single mode of action as the centerpiece of their weed management strategy (Frisvold and Reeves 2010; Norsworthy et al. 2012). Farmers saw improvements to yields and a reduction in input usage.

> The simplicity and flexibility of the GR crop/glyphosate combination to control virtually all weed species eliminated the need for consultants to provide prescription herbicide combination solutions dependent upon crop type, herbicide selectivity, and weed spectrum, even sometimes varying with different locations within a farm. Various surveys of farmers have found that the simplicity and flexibility of the GR crop technology has been one of the most important reasons for its adoption. (Duke and Powles 2009)

This simplicity also resulted in an increasing uniformity of growing conditions that lead to increased selection pressure for weeds that were resistant to glyphosate. This took place even though an integrated program rotation of crops, herbicides, nonherbicide weed controls, and cultural factors had been accepted for years by many in scientific and nonscientific communities as the preferred strategy for minimizing selection pressure and slowing down the process of evolution of resistance. More importantly, the development of this type of management system by and for human actors, underscores the importance of identifying the social and economic factors associated with herbicide resistance.

Social Factors. A major argument of our paper is that social and economic factors can not only help explain how herbicide resistance in weeds has emerged, but also must be part of the approach for addressing the associated environmental impacts. However, there has been virtually no empirical research that has collected information or analyzed the social factors that have contributed to the evolution of herbicide resistance. For example, a series of articles published in *Weed Technology* on farmer perceptions of herbicide resistance in six states (Givens et al. 2009; Johnson et al. 2009; Shaw et al. 2009) present valuable information on grower perceptions of the extent of the HR problem. But these studies did not conceptualize or measure the social conditions or processes that are known in the social science literature to sometimes influence human attitudes and decision making. Similarly, a study of Indiana growers (Johnston and Gibson 2006) relied primarily on farm size as a predictor of grower concerns about HR resistance. This parallels research done by natural scientists on IPM adoption (Hammond et al. 2006; Hollingsworth and Coli 2001) which are extensive in their description of self-reported grower practices, but which fail to theorize, or measure, important variables of sociological relevance. Some examples of the kinds of independent variables that could have been tested in these studies include the nature and strength of community ties (such as shared grower perceptions of what is going on in their fields), shared personal values (e.g., attitudes towards evolution, environmental stewardship, and neighboring farmers' well being), and the ways in which farms are incorporated into financial hierarchies (whether farmers have outstanding bank loans).

Subsequently, in this paper, we can only hypothesize as to what factors have been and could be significant in explaining how farmers perceive HR problems and the practices they are using. We suggest a few possible explanatory factors in hopes that these will be considered as interdisciplinary research projects on herbicide resistance are developed.

Social capital is one of several important theoretical constructs in the social science that has become an important theoretical concept for explaining various processes of social change and development, including innovation and adoption of agricultural practices, such as those deemed to be necessary for creating more sustainable agrifood systems. Social capital encompasses, but is not limited to, understandings of how people utilize trust, reciprocity, norms, rules, and sanctions to create networks for organizing/managing behavior (Pretty and Ward 2000), and enable social groups to collaborate on shared problems (Bodin et al. 2006), such as weed resistance. Thus, in an empirical study conducted in India, the decision on whether or not to use genetically engineered cotton seeds using *Bacillus thuringensis* (Bt) toxin by farmers was shown to be driven not only by a farmer's own experience with the technology, but also by the experiences of other farmers with whom a farmer interacted (Roy et al. 2007). This demonstrates why it is important to collect, as part of an analysis of HR, information on the social networks in which farmers participate and the types of knowledge and insights they receive from other farmers. In addition, understanding the structures of these networks and how they operate could be useful information for designing and disseminating information on new weed management approaches. The plausibility of such an approach is supported by ongoing research that has demonstrated that trust generated through social networks can lower the costs and barriers associated with learning about agribiodiversity (Pretty and Smith 2004).

Interaction in social networks, and the amount of trust and reciprocity that provide a foundation for particular networks, is related to how people create shared views about the problems they encounter as well as the potential solutions. The research of Brodt et al. (2006) has demonstrated not only that heterogeneity in management styles exists between groups of farmers, but that particular sets of goals and values shape the management styles that growers adopt. It is known that the adoption of HR seeds was shaped by farmers' economic and related nonpecuniary goals (Ervin et al. 2010). Thus, it is reasonable to assume that the adoption of alternative management practices for managing HR weeds might end up being influenced by the ways in which different farmers value the importance of holistic management practices as opposed to using a homogenous industrial approach. In other words, the "cultural lens" that groups of individuals develop not only shapes the way that they receive new information, but also how that information is understood and ultimately used (Bruckmeier and Tovey 2008). This suggests that not only is it important to study the strength of the social networks that people create (i.e., social capital) but that it is also necessary to identify the beliefs and attitudes people have about the social and environmental world around them that they use to filter the information they receive about new technologies and management practices.

Although the rationale behind the adoption of HR varieties, particularly with respect to the economic motivations of farmers, has been well studied, the social processes associated with their adoption in the United States, including analyses of the demographic and human capital characteristics of early adopters, has been less well analyzed (Ervin et al. 2010). However, since the work of Rogers (1995), it has been recognized that early adopters of new innovations are sometimes characterized by their high levels of human capital and a willingness to accept risk. Thus, it would be useful in efforts to promote alternative weed management strategies to assess whether farmers who express a willingness to try such approaches share these two characteristics.

Economic Factors. The economic factors contributing to pesticide resistance have been studied for decades (e.g., Miranowski and Carlson 1986) and the research continues (Frisvold et al. 2009). As noted above, the widespread adoption of GR and applications of glyphosate suggest that growers planting those varieties are experiencing significant economic benefits, including increased yields, and/or lower costs (Ervin et al. 2010). This substantial financial dividend is one of the main impediments to reducing glyphosate resistance buildup. In addition, a glyphosate strategy can deliver valuable nonpecuniary benefits to farmers, such as increased flexibility of farming operations for off-farm jobs and enhanced personal safety, in comparison to the use of other herbicides (Piggot and Marra 2008). Of course, these multiple advantages of glyphosate-only farming will be eroded as resistant weeds spread.

Overcoming the focus on substantial short-run economic advantages of using one dominant herbicide is a challenge for weed management professionals. A longer-term economic perspective likely will show a positive net value of multiple herbicide management, but individual farmers face short-run economic pressures to stay financially solvent. However, the increasing emergence of HR weeds suggests that many growers either do not recognize this economic advantage of an integrated approach, or other social factors inhibit their adoption.

The economics of managing HR weeds also involves consideration of herbicide manufacturers. Miranowski and Carlson (1986) show that the type of market structure that a pesticide manufacturer faces will affect the incentive for them to retard resistance development. A monopolist that sells a pesticide with no close substitutes will have a stronger incentive to protect the life of the compound than manufacturers who face a competitive market with close substitute pesticides. That means that the monopolist can charge a higher price for its pesticide compared to competitive markets, an action that will decrease the rate and extent of use over competitive conditions, and thereby conserve gene susceptibility to the compound. A final point Miranowski and Carlson (1986) considered was whether the market price of pesticides was signaling increasing scarcity of new pesticide products, and thus giving a market incentive to retard resistance development. They found the price of pesticides rose more slowly than for other agricultural inputs during the 1960 to 1980 period, thus indicating the steady introduction of new pesticide (substitute) products. Frisvold and Reeves (2010) report that same pattern continued through the 1990s up to 2008. However, given the small number of new herbicide products since the HR problems have proliferated, that price pattern might well be shifting (NRC 2012).

A final socio-economic factor affecting HR is the presence of CPR in the form of the weed gene pool susceptible to dominant herbicides. In their seminal article, Miranowski and Carlson (1986) analyzed the factors that will tend to exacerbate or retard both insect and weed resistance to pesticides. A key factor they focused on was the ability of a pest to move across a farm's boundaries, thus causing a common-pool externality, i.e., one farmer's insect control actions influence growers in the surrounding community. In the case of weeds, that pest mobility can happen through pollen dispersal and seed movement by mechanical means, such as transport on harvesting machinery. Initially, scientists seemed to believe that pest mobility was a more significant risk with insects (e.g., Gould 1995). However, recent experience and evidence suggests that certain

HR weeds are mobile (NRC 2012). A survey of Australian farmers found that 70% believed they had gained an HR problem due to the movement of weed seed or pollen (Llewellyn and Allen 2006). Importantly, their likely lower response to managing HR weeds would occur regardless of whether such biophysical movement had in fact occurred. The next section explores the implications of such pest mobility for creating a common-pool HR management problem and how private and public collective approaches, which are connected to social networks, can address it.

Common-Pool Resource Complications

The concept of the "tragedy of the commons," popularized by Garrett Hardin in the late 1960s (Hardin 1968), is probably well understood by most weed scientists. Hardin's central thesis was that natural resources owned in common will tend to be depleted or degraded because an individual user does not have to consider the full costs of their actions to other users or to the future. That is, other users will experience externalities in the form of lower resource quality, quantity and/or higher costs due to actions taken by the individual. The problem of individuals making decisions based solely on their self interest when their actions impact other users of the common resource pool lies at the heart of the tragedy of the commons. Recent research suggests, however, that this selfish behavior by farmers making conservation decisions with downstream consequences is not universal or uniform (Sheeder and Lynne 2011). In that research, they documented a significant empathetic effect by some farmers to undertake higher levels of conservation than would be predicted with standard economic profit maximization models. They conclude that these farmers might have dual objectives of pursuing economic benefits but also behaving in ways that are empathetic to their neighbors. The evidence for this social interconnection is another reason to incorporate the human dimension into HR research and management. The decline in ocean fisheries in international waters from unregulated harvesting is perhaps one of the best known examples of this type of breakdown in CPR management.

The weed gene population susceptible to particular herbicides can extend beyond individual farm boundaries and become a common-pool resource (NRC 2012; Webster and Sosnowskie 2010). Because some weed genes move across the landscape through pollen or seed movement by natural or mechanical processes, herbicide resistance can spread into a farm regardless of the operator's adoption of weed control BMPs. This common-pool effect has likely contributed to the recent spread of resistance to glyphosate. It could also hamper efforts to address the herbicide resistance problem because failure by nearly all farmers to adopt BMPs will mean that resistance likely will continue to spread to all farms. Despite the earnest efforts of public and private professionals to promote the use of BMPs farm by farm, increasing effort on such E&TA strategies for individual farmers will be insufficient to efficiently control the problem because of weed mobility.

A frequent misinterpretation of Hardin's thesis is that common ownership of the resource leads to excessive use or degradation of the natural resource. In fact, the attribute that leads to the excessive use pattern is open or unregulated access, not common ownership. A second misinterpretation of common property situations is that only public regulation can solve the overuse problem. Government regulation indeed can be used to address CPR overuse, as has happened with refuge requirements for Bt crops, but it might not be the most socially preferable or economically advantageous approach (NRC 2012).

Social scientists led by the late Elinor Ostrom, 2009 Nobel Laureate in Economics, have clarified that either public or private collective institutions can effectively regulate access to the CPR, depending on the particulars of the situation (Ostrom et al. 2012). Those scholars assembled evidence from a variety of CPR cases, such as managing groundwater aquifers that serve irrigation systems, to show how private collective institutions can effectively regulate resource use under certain conditions. We argue that their findings have direct relevance to developing effective approaches to control HR for cases involving interfarm HR weed pollen and seed mobility. Social scientists have distilled seven design principles from analyzing CPR situations that can inform collective HR management approaches (Ostrom et al. 2012).

1. *Clearly define the boundaries of the CPR.*—Boundary definition becomes crucial to institute collective management systems that facilitate exclusion of users or appropriators. In the HR case, this means identifying the set of growers whose actions affect the susceptible weed gene pool. Whether those boundaries can be drawn with accuracy sufficient to control the HR problem depends on the state of science about how specific weed genes move within a local area or region. If

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the boundaries cannot be defined accurately, effective exclusion cannot be guaranteed.

2. *Adapt rules to local conditions.*—There is no standard template for creating collective management institutions for CPR. However, some general principles will apply. First, a clear set of rules should define when and how much of the resource appropriators can access and under what conditions and these rules should be devised consistent with local conditions. A related principle is that the community's right of self-determination is recognized by higher authorities.

The access regime will depend on the biophysical and weed management particulars of specific situations (Llewellyn and Pannell 2009). This step implies that the local parties engaged in administering the management system must achieve consensus on those rules. Generally speaking, as the size and diversity of the group increases, the transaction costs of achieving that consensus will increase. As Ostrom and her colleagues explain:

> … a culturally homogeneous and relatively stable community where people have strong reputational and social ties and a commitment to long-term development is less likely to invite free-riding than a more mobile community with no strong sense of local or cultural identification. Groups which possess a high degree of interpersonal trust or social capital are more likely to arrive at commonly agreed rules and to adhere to these rules than are those lacking such social capital. If they are to be successful, therefore, the rules for resource management need to reflect this sociocultural variety. (Ostrom et al. 2012)

3. *Assure broad participation (i.e., most resource appropriators) through collective-choice mechanisms.*—Devising locally adapted rules to govern access is essential to achieving sufficient participation by appropriators to effect control of the CPR. The key question raised by this principle is "What level of participation is sufficient to deter the excessive depletion of the resource?" That answer depends mostly on the biophysical characteristics of the natural resource system. For HR issues, weed scientists must identify the minimum level of farmer participation that will keep HR from continuing to escalate. However, social scientists will play key roles in determining how best to achieve those minimum levels as explored in the final section.
4. *Implement monitoring accountable to the appropriators.*—The most successful private collective approaches to managing CPR have had strong monitoring mechanisms. This makes common sense because accurate information on compliance by appropriators is necessary to assess when the minimum levels of compliance are at risk of being breached. Making the monitoring accountable to the appropriators also has strong logic, because each will have a vested interest in assuring their neighbors' actions are accurately captured.
5. *Impose graduated sanctions for violating rules.*—The outcomes of monitoring lead directly to assessments of sanctions on those not meeting the rules of access and use of the CPR. The importance of graduated sanctions reflects the need to impose stronger incentives for compliance as the collective damages to the common resource, in this case weed susceptibility, increase. For HR issues, this could mean that the sanctions increase as the degree of BMP adoption lessens on a given land area and/or the application of BMPs cover less of the operator's land base, threatening negative spillovers to the farming community as a whole.
6. *Devise inexpensive and easy conflict resolution mechanisms.*—As for all resource governance systems, whether private or public, disputes about any number of aspects will emerge. This inevitability of conflict requires that clear and well-established rules are in place to resolve the disputes in simple and inexpensive ways. These procedures enhance the scope of possible decentralized solutions to CPR management problems (Ostrom et al. 2012). They also give the best chance of not resuming the scramble for resources that leads to the tragedy of the commons.
7. *Institute "polycentric" or nested layers of governance for larger CPR issues.*—A final key factor affecting the resolution of CPR problems is the constitutional relationships between different layers of decision-making, e.g., local, state, and federal. Ostrom's work demonstrated that effective rules of governance are more common in situations when those who have an immediate stake in solving CPR problems, generally the local appropriators, are active in shaping and enforcing those arrangements (Ostrom et al. 2012). However, when higher levels of government overrule or obviate the locally-devised systems, the management systems can become dysfunc-

> tional. This situation might arise when HR weed seed dispersal invades local areas through climatic or mechanistic (e.g., transport) processes, and requires higher levels of control. The premium on coordination of these multiple layers of approaches quickly becomes apparent. In short, it becomes critical for different centers (layers) to play different but coordinated roles.

The purpose of reviewing these design principles for this paper is to highlight the importance of human processes for managing a ''wicked'' problem such as weed resistance. Developing and implementing rules and procedures for weed management on a broad scale clearly require an understanding of social processes and networks. It also underscores how new technological advances alone will likely be insufficient for addressing the problem. The social processes by which new technological approaches are developed and disseminated are as important as the technologies themselves to addressing the environmental challenges of HR.

Insights from CPR Programs for HR Weed Management

To our knowledge, no CPR management program, either public or private, has specifically addressed HR weeds to this point. Nonetheless, a review of three CPR-related programs offers insights into the possible application to HR issues and challenges that might be confronted.

The first is the control of invasive (and/or noxious weeds) in the U.S. These programs are in essence an attempt to manage the genetic mobility of such weeds and therefore a CPR challenge. The formation of a weed management area (WMA) is a critical step to effective control of invasive weed management (Center for Invasive Plant Management 2002). Importantly, a WMA approach recognizes that a community-wide approach is essential to effective management because neighbors' actions affect neighbors' weed situations.

> The purpose of creating a WMA is to facilitate cooperation among all land managers and owners to manage a common weed problem in a common area, and thereby prevent the reproduction and spread of weeds into and within the WMA … WMAs have been successful throughout the West in controlling or even eradicating weed infestations that cross boundary lines and/or require expensive or intensive treatment. Weed Management Areas are also great vehicles for involving the community in a project that requires diligence and cooperation. (Center for Invasive Plant Management 2002)

WMA requirements reflect CPR design principles. For example:

> Establish clearly-defined boundaries coordinated with other WMAs. Boundaries of a WMA may be created according to: watersheds, topography, weed species, land usage, and/or rights-of-way. … Procedure for noncompliance must be followed where applicable. (Center for Invasive Plant Management, 2002)

The second example is the U.S. boll weevil eradication program that worked on eradicating the pest in cotton-producing areas. As noted already, insects have been recognized as mobile pests that create CPR issues. The boll weevil can travel long distances, so a regional approach was necessary. The program was administered by state departments of agriculture (regulation), the U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) for technical support, and the USDA's Cooperative States Research, Education, and Extension Services for information dissemination. This polycentric approach was necessary to assure sufficient conformance to program provisions across growers. Its costs were also shared between APHIS (30%) and producers (70%). Implementation of the program usually required cotton growers in an area of proposed expansion to pass a referendum by a two-thirds majority, and some states passed legislation to help defray some costs incurred by growers. Multiple long-term benefits flowed from the program, including significantly reduced insecticide usage and ensuing ecological benefits. The fundamental recognition of the common-pool nature of the problem drove this public–private collaborative approach and the requirement for extensive grower compliance to address a serious CPR issue.

The final brief example comes from growers' efforts to collectively manage their irrigation systems (Ostrom 1990). Waters used for irrigation are often CPR in which one grower's actions affect the amount of the resource available to other current and future users. This fundamental recognition has incentivized growers to find private collective solutions to managing their shared water resources in Spain, California, and Nepal rather than privatization or government programs. Ostrom

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et al. (2003) identified six lessons to inform the management of water rights in the commons that have import for HR management. Their third lesson, for example, that resource management should be thought of as a problem of designing a management system to meet an ongoing set of challenges reinforces the notion that the search for solutions to such "wicked problems" will require adaptive management.

Despite their promise, several limitations exist to implementing effective CPR approaches. Agrawal (2003) reviewed CPR research through the early 2000s to identify gaps in scientific knowledge and practice. His overarching conclusion was that scholars of CPR have too many variables that potentially affect resource management to analyze to provide clear guidance on effective implementation. For example, he found that the evidence on the size of group affecting the resource management has been equivocal, as opposed to the presumed advantage for smaller groups due to lower transaction costs, that a higher degree of group heterogeneity is not always a disadvantage, and that the effect of poverty on common resource use has not been uniform in effect. Apart from the problems with research methods, he concluded that the resource and political (social) contexts and differences in personal values are crucial in accounting for the variation in findings. This uncertainty in causal relationships emphasizes the importance of designing CPR institutions with the specific context in mind. In his view, generalizations about the influence of various drivers and institutional influences across CPR situations are not only difficult, but likely unwise.

Conclusions and Implications for Managing HR

Our discussion has advanced two central propositions about managing HR on U.S. farms to control potential deleterious environmental impacts. First, the causes and consequences of weed resistance to herbicides are the product of the interplay of biophysical, economic, and social factors with technology. By implication, any private or public program to control HR must address the combined effects of all factors in an integrated approach. Stacking more traits on GE crops so that multiple herbicides can be used if resistance emerges to one, will not get at the intertwined roots of this wicked problem and will at best lead to a delay in the advent of a variety of negative consequences. Indeed, just such a technology-focused approach has arguably led to the escalation of HR and reverting to it again will not address the core "wickedness" of the problem. Indeed, it could exacerbate the problem by delaying the development of holistic approaches that recognize the interconnections of biogeophysical, social, and economic dimensions of the issue.

The implications for HR management of recognizing the integrated nature of causes and solutions of the problem are profound. Coupled natural–human systems-based approaches are inherently complex and pervaded by uncertainty. Therefore, they will require experimentation and adaptive management to arrive at effective approaches. Adding to the complexity, the heterogeneity of farms and farmers means that successful approaches will not have fixed templates of practices but must adjust the nature of BMPs to the farm and operator situations. For example, small limited-resource operators who must devote significant time to off-farm employment will likely require different approaches than large industrialized operations. However, one clear message from the literature is the importance of building social and human capital so that farmers and weed science professionals can exchange ideas and learn from each other. Scientists and extension professionals who are working to disseminate more sustainable agricultural practices have long recognized the value of utilizing these forms of capital and might prove to be effective partners in efforts to develop and disseminate weed BMPs.

The second major proposition developed in this analysis is that reliance on individual farmer approaches will fail in the presence of HR weed pollen and seed mobility across farm boundaries that result in CPR problems. A large literature has shown that either private or public collective approaches will be necessary to solve such problems. These approaches are based on the recognition that human decision making is not only made by individuals, but also that individual decisions are invariably shaped by group social structures and conditions. Institutions that enable low-cost communication and coordination lie at the root of effective solutions to CPR challenges. Again, groups working to promote effective sustainable agricultural practices have long recognized the CPR aspects of agriculture and the necessity to build social capital capacity. Failing to address HR common-pool problems when present will result in frustration for operators and professionals and wasted resources all around.

Research has documented that either the private or the public sector can evolve sustainable solutions to CPR challenges. Some form of regulated access to the CPR is a common public approach, such as those that have been implemented to manage ocean fisheries. Such public regulatory approaches can work to reverse resource depletion, but can also induce inefficiencies and inequities among producers if uniform rules or technological approaches are applied to heterogeneous appropriators. However, managing HR poses special challenges because of the nonpoint nature of the externalities involved and the heterogeneity of the biophysical and social conditions of the farms contributing to the problem; thus, a private approach to managing the common resources might be more cost effective. One such option would be to promote private collective action utilizing the design principles derived from CPR situations in the United States and abroad. Ample evidence exists to suggest that private approaches can work if certain conditions are met. A private approach possesses the potential to incorporate flexibility in approaches that accommodate producer heterogeneity and lower compliance costs, while encouraging continuous innovation. It could also involve coordinated layers of governance from local producer HR management organizations for monitoring to commodity organizations and universities or government for delivering technical assistance.

Regardless of the approaches that will be tried to control HR, the task of devising effective solutions to herbicide resistance is enormously challenging. The ''wicked problem'' framework and our review of some of the likely social and economic factors associated with this problem suggest that sustainable HR management will require new interdisciplinary research and outreach involving growers, and intense collaboration among all stakeholders to the issues. This interdisciplinary approach will need to include social and economic scientists as well as weed scientists and other professionals involved in agricultural weed management. Although such an approach will not guarantee success, it is highly likely that success will not be achieved without incorporating the human dimensions of weed resistance into strategies aimed at promoting holistic systems of BMPs.

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