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Herbicide-resistance management: a common pool resource problem?

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Abstract

Herbicide resistance is often viewed as a complex problem in need of innovative management solutions. Because of the transboundary mobility of many weeds, resistance to herbicides is also viewed as a community-scale issue. Consequently, the idea of greater coordination among resource users—especially growers—is often promoted as a management approach. Recently, scholars have framed herbicide resistance as a commons problem in need of collective action. Specifically, social scientists have explored the utility of adopting bottom-up, community-based approaches to help solve the growing problem of herbicide resistance through a framework for interpreting the commons known as common pool resource theory. This article analyzes how herbicide resistance fits—and fails to fit—within common pool resource theory and offers an updated conceptual framework from which to build future work. We argue that the application of common pool resource theory to herbicide-resistance management is underdeveloped, and approaches based on this theory have shown little success. The relevance of common pool resource theory for informing herbicide-resistance management is less settled than existing scholarship has suggested, and other frameworks for approaching transboundary resource problems—such as co-production of knowledge and participatory action research—warrant consideration.

Introduction

The resistance of weeds to herbicides is an increasing problem in North America, Europe, and in many other locations around the world (Pannell et al. 2016; Peterson et al. 2018). Since the end of World War II, many agricultural systems have become reliant on herbicides for weed management (Davis and Frisvold 2017; Norsworthy et al. 2012). Associated declines in the efficacy of herbicides threaten current agricultural production systems, posing significant economic costs and threatening food security at multiple scales (Ervin et al. 2019; Espig et al. 2022). Currently, weeds have evolved resistance to more than 150 herbicides (Beckie et al. 2021). Widespread resistance to the herbicide glyphosate poses particularly significant challenges, because global food production relies heavily upon it. Thus, glyphosate-resistant weeds draw attention to the problem of herbicide resistance and create an urgency for management solutions (Bain et al. 2017; Duke and Powles 2008).

Herbicide resistance is an evolutionary process that can occur with any weed species–herbicide combination (Heap 2014; Shaw 2016). While early examples of herbicide resistance dating back to the early 1950s exist, a golden age of herbicide discovery from the 1950s through the 1980s allowed for significant management flexibility and buffered against risks associated with the declining efficacy of certain herbicides (Beckie et al. 2019; Duke 2012). Herbicide resistance is not a significant pest management concern if new, economically viable herbicides become available. However, a lack of new herbicide modes of action and agricultural systems overly dependent on herbicides for weed control have laid the foundation for the sociobiological problem of weed resistance (Gould et al. 2018). The development and rapid adoption of glyphosate-resistant crops (i.e., soybean [*Glycine max* (L.) Merr.], corn [*Zea mays* L.], cotton [*Gossypium hirsutum* L.], canola [*Brassica napus* L.], sugar beet [*Beta vulgaris* L.]) beginning in the mid-1990s has not only increased the rapidity of weed resistance evolution to glyphosate but also worked to limit the economic viability of herbicide discovery (Beckie et al. 2019; Davis and Frisvold 2017; Duke 2012).

To solve contemporary management problems related to weed resistance, scientists and managers commonly turn to the concept of integrated weed management (Moss 2019). Integrated weed management is predicated on adopting a diverse set of weed control tactics to help growers control resistance, including strategies such as crop rotation, tillage, and herbicide combinations (Owen et al. 2015). This approach guided the response to a significant herbicide-resistance crisis that began in Australia during the 1990s in relation to rigid ryegrass (*Lolium rigidum* Gaudin) (Llewellyn et al. 2007). Emergence of significant resistance limited the efficacy of simple herbicide control tactics and forced many growers into a more diversified weed management approach. Specifically, Australian growers have blended various chemical, mechanical, and cultural techniques to keep resistant populations of *L. rigidum* controlled at an economically acceptable level (Peterson et al. 2018; Walsh and Powles 2014). In the United States, integrated weed management serves as the conceptual core behind best management practice recommendations to mitigate the development and spread of herbicide-resistant weed populations (Lyon et al. 2019; Norsworthy et al. 2012). Ultimately, these best management practices inform education and technical assistance programming, which serves as the dominant approach to improving herbicide-resistance management, and weed management more broadly, in the United States (Schroeder et al. 2018).

The purported ineffectiveness of traditional education and technical assistance approaches to curb the growth and spread of herbicide-resistant weeds in the United States is frequently used as justification to develop alternative solutions to management (Jussaume and Ervin 2016). An emerging body of scholarship argues that community-based solutions to herbicide resistance may offer a path forward to manage herbicide resistance (Dentzman 2021; Ervin and Jussaume 2014; Shaw et al. 2018). Grounded in a conceptualization of weed susceptibility to herbicides as a commons problem because of the transboundary mobility of weed seed and pollen, this scholarship draws from common pool resource theory and analysis of cooperative pest management programs to support and inform bottom-up, community-based governance approaches (Ervin and Frisvold 2016; Shaw et al. 2023). This framing, however, fails to account for certain physical and social dynamics associated with herbicide resistance that may limit its utility as the basis for community-scale management solutions. This article lays out ways that herbicide resistance fits—and fails to fit—within common pool resource theory and offers an updated conceptual framework from which to build future work.

Identifying Herbicide Resistance as a Commons Problem

Taking a cooperative approach to addressing the transboundary nature of pests is a well-established landscape-level management strategy (Fiege 2005; Klassen 2000). A major rationale for collective pest management rests with the idea that coordinated strategies—as compared with individual action—can better keep a total pest population below a threshold of concern (Elliott et al. 2009; Hueth and Regev 1974). With regard to resistance management, pest mobility is understood as key in determining whether individual or collective management is a preferable strategy (Ervin and Frisvold 2016; Miranowski and Carlson 1986). In an influential paper Miranowski and Carlson (1986) argue that pest susceptibility should be conceptualized as a type of commons resource because of its mobility. However, their essay focused specifically on insect resistance to insecticides, and it is only in the last two decades that social science scholarship in Australia and the United States has recognized the implications of mobility for creating a potential herbicide-resistance commons problem.

The earliest significant economic concerns associated with herbicide resistance occurred in Australia (Harrington and Ghanizadeh 2023; Pannell et al. 2016). Consequently, much of the original scholarship examining weed resistance mobility and its management outcomes came out of this context. *Lolium rigidum* poses the largest resistance concern for Australian cropping systems. Importantly, the biophysical properties of *L. rigidum* vis-à-vis its interactions with certain herbicides largely shaped the management response. Specifically, *L. rigidum* "possessed a remarkable ability to rapidly evolve resistance to multiple selective herbicides without suffering any fitness penalty" (Pannell et al. 2016, 136). The speed and uniformity of resistance evolution meant that despite the detrimental spread of resistant *L. rigidum* across the landscape, potential benefits of cooperative approaches were low. Two different types of mobility influence the viability of community-based management for herbicide resistance: external spread (i.e., movement of weed seed and pollen) and internal mobility (i.e., independent resistance evolution coupled with widespread infestation). In the Australian context, the ability to manage the weed resistance commons through individual management strategies and innovations was effective—at least in the short term—and economic modeling determined that little incentive existed for a landscape-level management approach.

Although economists evaluated cooperative management of herbicide resistance as a nonoptimal strategy in the Australian context, some scholarship—relying on a broader body of work related to pest management (i.e., insects)—recognized the potential benefits of a proactive cooperative management approach. Llewellyn and Allen (2006) identified that further resistance management concerns could come from rarer forms of herbicide resistance. Consequently, they offered a critique of existing Australian research and extension strategies that did not sufficiently address the mobility of resistance. Specifically, they realized that grower perceptions of resistance mobility—independent of biological reality—could be enough to create a collective action problem. To address this concern, Llewellyn and Allen (2006) called for more research to determine the reality of resistance conditions and suggested that cooperative management could be appropriate in some cases. While the authors helped lay the foundation for conceptualizing herbicide resistance as a collective action problem, they did not offer any analysis into the functioning of cooperative management as a governance framework.

The resistance literature conceptualizing pest management as a common property resource as well as social science scholarship in the Australian context helped inform subsequent scholarship emerging primarily in the United States focused on community-based management approaches to addressing herbicide resistance (e.g., Bagavathiannan et al. 2019; Ervin and Frisvold 2016; Evans et al. 2018). As part of a larger literature focusing on incorporating social science methods and analysis into herbicide-resistance management (e.g., Dentzman 2022b; Jussaume and Ervin 2016), this scholarship has largely adopted common pool resource theory (e.g., Ostrom 1990; Schlager 2004) as an updated lens through which to understand herbicide resistance as a commons problem. Although we support the integration of common pool resource theory into resistance management scholarship, we argue that analysis of this integration is underdeveloped. Situating herbicide resistance as an open access common pool resource problem conveniently allows scholars to both equate the issue to Garett Hardin's tragedy of the commons thesis and to turn to Elinor Ostrom's work on governing common pool resources to investigate the utility of community-based policy solutions (Ervin and Frisvold 2016; Ervin and Jussaume 2014; Ervin et al. 2019; Shaw et al. 2023), but certain elements of this application fail to account for the complexities of herbicide resistance.

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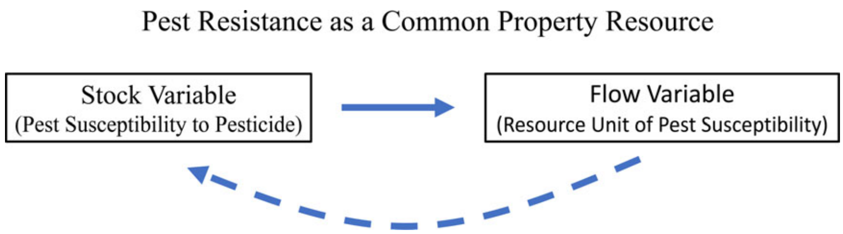

Figure 1. Diagram of pesticide resistance as common property resource based on Miranowski and Carlson (1986). In this conceptualization, the common property resource is pest susceptibility, which is composed of a stock variable and a flow variable. Pest resistance is initially a renewable resource but becomes depleted over time through repeated use of chemicals. Thus, the actions of certain individuals may deplete the resource stock for others.

Consequently, in the following sections, we review previous applications of common pool resource theory to herbicide-resistance management with the goal of furthering conceptual understandings of herbicide resistance as a transboundary resource and sharpening management strategies for successful governance.

Situating Herbicide Resistance within Common Pool Resource Theory

The "commons" is not only a deceptively complex conceptually but also has a contested history and meaning (Bromley 1992; McCarthy 2009). Because there is no universal definition of the commons, it is worthwhile to trace its use and meaning with respect to herbicide-resistance management. Earlier scholarship on resistance management used an ownership framework (i.e., common property resource) for defining the commons (e.g., Llewellyn and Allen 2006; Miranowski and Carlson 1986). One of the strengths of common pool resource theory is that it conceptually breaks the commons into two components: resource system and institutional governance structure (McCarthy 2009; Ostrom et al. 1999; Schlager and Ostrom 1992). This separation provides clarity on the differences between resource characteristics and institutional arrangements for governing resources. Furthermore, common pool resource theory employs a typology of goods framework. In this framing, excludability (i.e., difficulty of excluding those who benefit from use of the resource system) and subtractability (i.e., whether a resource unit is available for joint use)—not ownership—are the primary criteria used to define a common pool resource (Ostrom 1990; Ostrom et al. 1999). Although some scholars argue for defining herbicide resistance as a public goods problem (e.g., Bagavathiannan et al. 2019), a common pool resource framing is the dominant approach to conceptualizing community-based herbicide-resistance management (e.g., Evans et al. 2018; Gould et al. 2018; Haywood et al. 2021; Shaw et al. 2023).

The explicit adoption of common pool resource theory to improve herbicide-resistance management is more recent than the literature suggests. Social scientists first characterized herbicide resistance as a common pool resource problem in the 2010s and suggested that Ostrom's design principles could inform collective management approaches (Ervin and Frisvold 2016; Ervin and Jussaume 2014). This scholarship relied primarily on an earlier interpretation of insect resistance from common property theory to conceptualize herbicide resistance as a common pool resource problem. Miranowski and Carlson (1986) identified the susceptibility of a pest to a pesticide as the shared resource of concern and conceptualized pest susceptibility as a stock variable (Figure 1). In this framing, the stock of pest susceptibility is initially a renewable resource, and its resource units (flow variable) can be harvested repeatedly. However, the repeated use of chemicals to control pests will eventually lead to resistance that will not only subtract from the stock of pesticide susceptibility but could potentially lead to total depletion. Influentially, Miranowski and Carlson (1986) argued that the degree to which pesticide resistance can be understood as a commons problem is not fixed but varies based upon its mobility. In other words, a highly mobile pest that moved between farms would create a shared resource problem, whereas an immobile pest that did not move between farms would constitute an individual resource problem. Miranowski and Carlson (1986) shared a similar natural resource economics approach with common pool resource theory for conceptualizing a resource system; however, the use of Miranowski and Carlson (1986) has led to a simplified and incomplete understanding of herbicide resistance where the sole stock variable (i.e., commons resource) is the weed gene pool susceptible to herbicides (Ervin and Frisvold 2016). Consequently, existing community-based herbicide-resistance literature has not properly accounted for the herbicide itself as a separate but interconnected common pool resource system, where the herbicide is a subtractable resource and excluding others from benefits of its use is very costly. Although some scholarship mentions efficacy of herbicides as an exhaustible or finite resource (e.g., Davis and Frisvold 2017; Ervin et al. 2019), no conceptualization of herbicide efficacy as a stock variable occurs in the existing literature.

In our interpretation of herbicide resistance as a common pool resource problem, two coupled common pool resources exist: a herbicide and a weed gene pool (Figure 2). Furthermore, four distinct but interrelated stock variables exist: (1) supply of a herbicide; (2) supply of a weed gene pool susceptible to a herbicide; (3) supply of a weed gene pool resistant to a herbicide; and (4) the supply of herbicide efficacy on a weed gene pool. In accordance with common pool resource theory (e.g., Ostrom 1990), we also include corresponding flow variables.

When interpreting our conceptualization of herbicide resistance as the product of two coupled common pool resources, it is important to begin with the herbicide itself. This resource is manufactured outside the resource use area and is purchased by the resource user. In the act of applying the herbicide, the resource user appropriates the resource unit. The act of applying the herbicide directly influences the second resource system—the weed gene pool. The weed gene pool can be conceptualized as consisting of genes susceptible and/or resistant to the herbicide. The use of a herbicide application (F1) influences the weed gene pool. However, the weed gene pool (S2 and S3) also acts independently of herbicide use and depends on both biological dynamics and social dynamics. Importantly, dynamics involving the weed gene pool are complex and include spatial and temporal variability in both the plant population and weed seedbank. The characteristics of the weed gene pool then affect the efficacy of the herbicide (S4), determining

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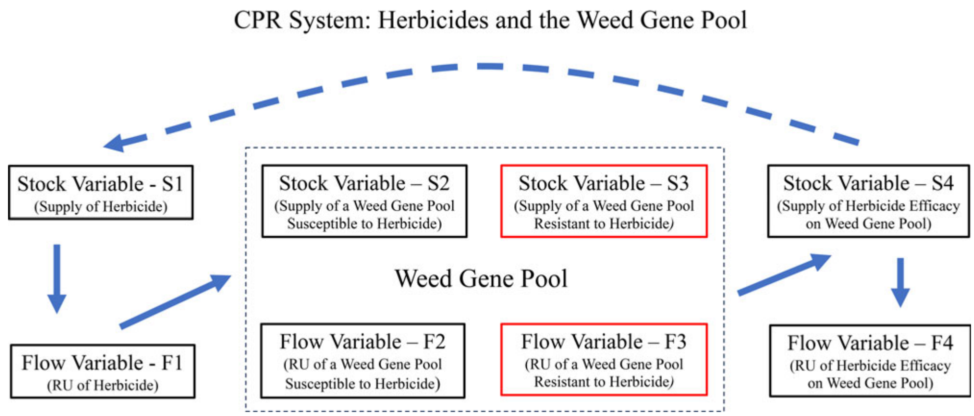

Figure 2. This diagram conceptualizes herbicide resistance as a common pool resource problem. Importantly, two conjoined common pool resources—herbicides and the weed gene pool—make up this resource system. Following common pool resource theory, this diagram illustrates the interconnectedness of four stock variables: (1) supply of a herbicide; (2) supply of a weed gene pool susceptible to a herbicide; (3) supply of a weed gene pool resistant to a herbicide; and (4) supply of herbicide efficacy on a weed gene pool. We have also diagramed corresponding flow variables or resource units (RU). In a generalized way, the use of a herbicide application (F1) influences the weed gene pool. However, the weed gene pool (S2 and S3) also acts independently of herbicide use and is influenced by both biological dynamics and social dynamics. Importantly, dynamics involving the weed gene pool are complex and include spatial and temporal variability in both the plant population and weed seedbank. The characteristics of the weed gene pool (S2 and S3) then affect the efficacy of the herbicide (S4) and whether its effectiveness is renewable or whether it becomes a finite stock resource. The quality of the herbicide (S4) may ultimately affect the supply of the herbicide (S1), if declining efficacy takes away from the herbicide's economic and chemical utility. In particular, the quality of these two common pool resources and not simply the quantity makes it a very complex resource arrangement. Factors adding complexity include that the weed gene pool is simultaneously both a pest and a resource. Furthermore, when the weed gene pool is characterized as a resource (its susceptibility to herbicides), the quality of this resource depends primarily upon provisioning practices of the common pool resource that keep the quality intact. In other words, following resource practices that do not allow internal or external resistance into the gene pool is key to maintaining its quality. The lack of quality from underprovisioning may result in a finite stock supply of the resource (i.e., weed gene pool susceptible to herbicides). Overappropriation (i.e., quantity or overharvesting of the resource) is a concern, in that it can be connected to poor provisioning practices. Aside from using a resource unit of herbicide in an application, the resource user does not directly appropriate or harvest from the system. This schematic only covers a generalized scenario, and more fine-scale analysis is needed to tease apart the complex relationships existing among herbicides and the weed gene pool.

whether its effectiveness is renewable or whether it becomes a finite stock resource (here we define herbicide efficacy as a resource that depends exclusively on the composition of the weed gene pool and not on other environmental or social variables). The quality of the herbicide (S4) may ultimately affect the manufactured supply of the herbicide (S1) if declining efficacy takes away from the herbicide's utility and profitability.

The quality—in addition to the quantity—of these two common pool resources increases the complexity of the system. Factors adding complexity include that the weed gene pool is simultaneously both a pest and a resource. Furthermore, when the weed gene pool is characterized as a resource (its susceptibility to herbicides), the quality of this resource depends primarily upon provisioning practices of the common pool resource that keep the quality intact. In other words, following resource practices that do not allow internal or external resistance into the gene pool is key to maintaining its quality. The lack of quality from underprovisioning may result in a finite stock supply of the resource (i.e., weed gene pool susceptible to herbicides). Overappropriation (i.e., quantity or overharvesting of the resource) is a concern, in that it can be connected to poor provisioning practices. Aside from using a resource unit of herbicide in an application, the resource user does not directly appropriate or harvest from the system. This schematic only covers a generalized scenario and more fine-scale analysis is needed to tease apart the complex relationships existing among herbicides and the weed gene pool.

Our framework makes conceptualization of herbicide resistance's resource characteristics more complex and its implications for governance less straightforward. This understanding is relevant, because contemporary herbicide-resistance management literature relies significantly on common pool resource theory to offer governance solutions. While we do see evidence to suggest that weed susceptibility to herbicides exhibits defining characteristics of a common pool resource, we argue that current herbicide-resistance management literature has not adequately conceptualized its resource characteristics. The weed–herbicide resource system is different from those used in the development of common pool resource theory (i.e., pastures, inshore fisheries, forests), and thus the application of common pool resource theory to herbicide-resistance management requires additional analysis. We offer this new conceptualization of herbicide resistance—as two coupled common pool resources that consist of four distinct but interrelated stock variables—with the goal of initiating further scholarly development of herbicide resistance's resource characteristics to help better inform management strategies.

Applying Common Pool Resource Theory to Herbicide-Resistance Management

Common pool resource theory separates the commons into resource system and institutional governance structure. This creates a need to also analyze how existing herbicide-resistance management scholarship has applied common pool resource theory to inform governance possibilities. Although scholars in Australia previously identified herbicide resistance as a possible commons problem, this scholarship did not provide analysis of collaborative governance approaches for managing the trans-boundary characteristics of herbicide resistance. Instead, Ervin and Jussaume (2014) and Ervin and Frisvold (2016) provided the first significant analyses of community-based governance options for herbicide-resistance management. These two articles formed the foundation for a growing community-based management scholarship for herbicide resistance. Grounding their analysis in the idea that sufficient mobility can make weed susceptibility to herbicides an open access commons resource subject to overuse (i.e., tragedy of the commons), Ervin and Frisvold (2016) lay out three possible

Common Pool Resource Attributes

Feasibility Improvement	Indicators	Predictability	Spatial Extent
Resource conditions are not at such a point of deterioration that it is useless to organize, nor are they so underutilized that little advantage results from organizing.	Reliable and valid indicators of the condition of the resource system frequently are available at a relatively low cost.	The flow of resource units is relatively predictable.	The resource system is sufficiently small, given the transportation and communication technology in use, that appropriators can develop accurate knowledge of external boundaries and internal microenvironments.

Figure 3. Attributes of common pool resources associated with cooperative behavior and self-governance. Adapted from Schlager (2004, 151–152).

Resource User Attributes

Salience	Common Understanding	Low Discount Rate	Trust and Reciprocity	Autonomy	Prior Organization Experience and Local Leadership
Appropriators are dependent on the resource system for a major portion of their livelihood or other important activity.	Appropriators have a shared image of how the resource system operates and how their actions affect each other and the resource system.	Appropriators use a sufficiently low discount rate in relation to future benefits to be achieved from the resource.	Appropriators trust one another to keep promises and relate to one another with reciprocity.	Appropriators are able to determine access and harvesting rules without external authorities countermanding them.	Appropriators have learned at least minimal skills of organization and leadership through participating in other local associations or through studying ways that neighboring groups have organized.

Figure 4. Attributes of resource users associated with cooperative behavior and self-governance. Adapted from Schlager (2004, 152).

solutions to avoid resource overuse and degradation: (1) top-down government regulation; (2) incentive payments; and (3) bottom-up, community-based approaches. After providing explanation for why the first two are unlikely to succeed for herbicide resistance, the authors turn their attention to community-based approaches. Specifically, their analysis centers on one component of common pool resource theory and four community-based approaches within agriculture. In this section, we review the use of common pool resource theory in these papers and offer further analysis on the relevance of common pool resource theory to herbicide-resistance management.

When engaging with common pool resource theory, Ervin and Jussaume (2014) and Ervin and Frisvold (2016) focus the majority of their attention on the promise of the theory's eight design principles for informing herbicide-resistance management. Although this is not necessarily an incorrect approach, it is important to understand that Ostrom (1990) derived these principles from studying two specific types of renewable common pool resource systems: mountain commons in Switzerland and Japan and irrigation commons in Spain and the Philippines. The design principles are indicative of the likelihood of successful and long-lasting common pool resource institutions, and they were not derived with the intention of serving as a road map for designing a community-based management effort. As Ostrom (2012) wrote in an essay more than two decades after proposing the design principles, "At times, I think that I should have called them something else because people confused that term with the idea that we are trying to design something from the beginning. However, I was really undertaking a study of robustness of systems that already existed" (77). Ervin and Jussaume (2014) and Ervin and Frisvold (2016) analyze the design principles to articulate the components of a successful community-based approach to herbicide-resistance management. As Ervin and Frisvold (2016) state, "Understanding the content of each principle is critical to building successful community-based programs" (613). Although it is possible that applying insights from the design principles might provide a creative solution for a successful community-based strategy for herbicide resistance, this method has its limitations as a post hoc approach.

By focusing on building successful management institutions through the design principles, Ervin and Jussaume (2014) and Ervin and Frisvold (2016) largely steered away from evaluating whether the necessary conditions exist for collective action to herbicide resistance at a community scale. Although Ervin and Frisvold (2016) featured a version of common pool resource theory's 10 attributes influencing whether users will self-organize to manage a common pool resource, these authors did not systematically analyze the relevance of these attributes to the potential for community-based herbicide-resistance management. Developed after the design principles, these 10 attributes represent a shift in Ostrom's work on common pool resource scholarship away from "explaining the conditions that support long-term cooperation and coordination among appropriators" and toward "identifying the conditions under which appropriators are likely to cooperate to devise governing arrangements" (Schlager 2004, 151). These 10 attributes (Figures 3 and 4) were revised and then incorporated into Ostrom's later framework on socioecological systems (Ostrom 2009).

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The first four common pool resource attributes listed in Figure 3 are suggestive of the daunting challenges facing grower-led, community-based approaches to herbicide-resistance management. The lack of visibility and the mobility of the weed gene pool means that accessing reliable, timely, and low-cost indicators of herbicide resistance present in the weed gene pool is difficult to achieve. The same challenges related to indicators influence the predictability and the flow of resource units. The flow of the herbicide resource unit is predictable, but the flow of resource units associated with the susceptibility of the weed gene pool to a herbicide and herbicide efficacy on the weed gene pool becomes much less predictable when resistance is present. In other words, internal or external spread of resistance largely determines both the susceptibility of a weed gene pool to herbicides and herbicide efficacy on a weed gene pool within a field and farming operation. The difficulty of predicting internal or external spread makes proactive management challenging. Depending on the type of resistance that develops in an area, a more reactive community-based approach might be more feasible, such as the community-based attempt to manage herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) (Barber et al. 2014). However, many barriers exist for reactive community-based management, including readily available indicator data showing the spatial extent and spread of resistance. The lack of good data is both a technical problem and a social one (Endres and Schlessinger 2016; Rissman et al. 2017). Even if the spatial distribution is known, the willingness of growers to share information that may negatively affect land values is a potential barrier.

The six attributes associated with resource users listed in Figure 4 further indicate the obstacles to grower-led collective action emerging to address herbicide resistance. The salience of preserving weed susceptibility to herbicides and herbicide efficacy to weeds is not insignificant but variable across farming communities. For example, herbicides are more important in conservation tillage systems as compared with conventional tillage systems (Dentzman and Burke 2021). Furthermore, there are perceptual barriers to action that affect salience. For instance, many growers are technological optimists who expect future herbicide discovery or alternative weed control technologies to solve the problem (Dentzman and Jussaume 2017; Llewellyn et al. 2007). The complexity of the resource system and the limited knowledge of the resource contributes to a lack of shared understanding among growers regarding herbicide-resistance management. The attributes of trust and reciprocity among resource users as well as local leadership will vary greatly by place and face the common cultural barrier of individualist orientations (Dentzman and Jussaume 2017).

In summary, it is important to recognize that these attributes associated with common pool resource user cooperative behavior and self-governance are not determinates of collective action, and common pool resource theory is not the only conceptual framework through which we can understand transboundary resource problems. However, the prospect of collective action for herbicide-resistance management as informed through common pool resource theory is not promising, and no sustained example of a commons governance framework for herbicide-resistance management exists, despite the presence of herbicide resistance as a resource problem for more than 30 years. Common pool resource theory's 10 attributes offer insight into why very little grower-led collective action to address herbicide resistance has occurred. Becoming more familiar with the conditions underlying the likelihood of grower-led collective action from common pool resource theory may help better inform understanding of how additional external actions—such as university-led voluntary coordination or legislative policy changes—could improve the prospects of community-based solutions to herbicide-resistance management.

Conclusion: Looking Back to Look Forward

Throughout this article, we have focused our analysis on the treatment of common pool resource theory within scholarship surrounding community-based herbicide-resistance management. This framework proved influential for informing scholarship analyzing the utility of voluntary, bottom-up approaches to herbicide-resistance management. However, we argue that the application of common pool resource theory to herbicide-resistance management is underdeveloped, and approaches based on this theory have shown little success. The relevance of common pool resource theory for informing herbicide-resistance management is less settled than existing scholarship has suggested, and other frameworks for approaching transboundary resource problems—such as co-production of knowledge (e.g., Landström et al. 2011; Norström et al. 2020) and participatory action research (e.g., Keahey 2021; Whitman et al. 2015)—warrant consideration.

Co-production of knowledge and participatory action research are collaborative research approaches that elevate the legitimacy of experiential knowledge and other ways of knowing with scientific expertise and methods. These approaches rely on multiple stakeholders—including scientists and nonscientists—to generate new research and knowledge that is actionable and may create transformational change (Cornish et al. 2023; Wyborn et al. 2019). In the context of weed management, these two community-based research methods may enable the creation of novel ideas to address herbicide resistance that are place specific and could improve management practices and outcomes (Dentzman 2022a; Jordan et al. 2016; Staver 2001). Rather than leading a community-based herbicide-resistance intervention that is focused exclusively on improving management outcomes, these types of approaches—centered on research collaboration—are more commensurate with the skills and expertise of university weed scientists.

Aside from integrating other community-based frameworks such as co-production of knowledge and participatory action research into herbicide-resistance governance, gaining an improved understanding of characteristics of the resource itself is important to inform future herbicide-resistance management strategies. Improving both general and site-specific knowledge of how herbicide resistance functions as a transboundary resource should help more accurately inform the debate between the utility of individual versus cooperative management approaches. Furthermore, understanding resource characteristics may offer insights into what type of community-scale management approach may work best. External regulatory mechanisms could be explored as an impetus for resource users to develop their own local rules for managing the transboundary problem of herbicide resistance, as governance solutions often work best when drawing on a mixed portfolio of policy tools (Doremus 2003; Gaymer et al. 2014; Koontz and Newig 2014).

There is little doubt that declining weed susceptibility to herbicides and herbicide efficacy to weeds represent a growing management concern across the globe. However, we caution both scholars and practitioners against acting too hastily. With respect to community-based management of herbicide resistance, we believe further research is needed to assess the most effective solutions to the problem. While there is existing scholarship supporting cooperative management approaches to herbicide resistance, other (potentially better) mechanisms may exist for influencing herbicide resistance across a community-scale. We acknowledge that our perspective is not without its own set of assumptions and weaknesses and welcome future research and discussion to help generate more fruitful paths forward for managing weed resistance across the landscape.

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