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A Growing Common Challenge: Herbicide Resistance and Farmers' Attitudes Toward Collective Management in Argentina

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Prior to the emergence of herbicides, farmers mainly used mechanical methods to control weeds around their crops. But these practices are energy-, labor-, and time-intensive (Shaw et al., 2012). By adopting herbicides, farmers were able to reduce the costs of controlling weeds, soil erosion, and energy consumption while increasing the capture and storage of carbon dioxide in the soil (Jussaume and Dentzman, 2016; Van Deynze, Swinton, and Hennessy, 2022). A new era in weed management began in the 1990s with the advent of commercial row crops that were genetically engineered to be herbicide-tolerant (HT) (Dill, 2005). Farmers were able to control weeds in their fields with just one chemical by planting crops tolerant to glyphosate, a broad-spectrum herbicide that at the time successfully killed most weeds (Swinton and Van Deynze, 2017).

As a result of the benefits HT soybeans offered in terms of reduced expenses and simpler weed management, farmers in developed and technologically advanced developing nations quickly adopted this technology. By 2004, the United States and Argentina ranked first and second, respectively, in terms of the percentage of area planted to genetically modified crops in countries around the world (Sexton, Lei and Zilberman, 2007). In the United States, the area devoted to planting HT soybeans increased from 7% in 1996 to more than 90% in 2007 (USDA-ERS, 2023); in Argentina, HT soybeans accounted for over 90% of the total area devoted to soybeans within 4 years of being introduced (Penna and Lema, 2003). Currently, the United States and Argentina are the world's second- and third-largest soybean producing countries, respectively (FAOSTAT, 2024).

The widespread adoption of glyphosate-resistant crops resulted in a change in the approach that farmers used to manage weeds, moving away from a broad set of mechanical, biological, chemical, and cultural practices toward a system typically comprising glyphosate applications alone (Duke and Powles, 2008). As a result, glyphosate became the primary, and often the only, herbicide applied for controlling weeds in soybeans and corn (Vila-Auib et al., 2008). This dependency on glyphosate—the most commonly used herbicide in the world, with an estimated 8.6 billion kg applied globally each year (Landau et al., 2023)—imposed strong selection pressure on weed populations. The problem occurred because weeds tend to develop tolerance to herbicides when farmers regularly administer the same chemical instead of changing the mode of action. Each farmer has a short-term incentive to use an herbicide without taking into account its consequences on the development of resistance (Bagavathiannan et al., 2019), thereby contributing to reducing the stock of efficacy of the chemical to treat a pest, which is a shared resource among all farmers in a region (Regev, Gutierrez, and Feder, 1976). Thus, weed susceptibility is vulnerable to the tragedy of the commons. Interestingly, pesticides are being used as if weed resistance were a transient problem that will be solved by new chemicals in the future, notwithstanding the fact that no herbicides with novel modes of action have been introduced in the last 30 years (Gould, Brown, and Kuzma, 2018). In North America alone, the cost due to the reduction in crop output associated with the loss of glyphosate as an effective tool to control weeds has been estimated at $4.17 billion per year (Brookes, Taheripour, and Tyner, 2017).

The first glyphosate-resistant weed in the United States was documented in 2000 (VanGessel, 2001); in Argentina, the first case of a weed that showed glyphosate resistance was reported in 2005. Currently, the number of cases in both countries has increased to 18 (Heap, 2023). Typically, weeds are less mobile pests compared to insects. However, new evidence suggests

that weed mobility is more significant than originally thought (Michael, Owen, and Powles, 2010). Weed mobility may be caused by pollen drift from herbicide-resistant weeds (Jhala et al., 2021), by the movement of seeds associated with human activities (for example, when weed seeds piggyback on machinery employed across different farms, counties, and states, McCanny and Cavers, 1988), by weed seeds drifting down creeks and rivers (Ervin and Frisvold, 2016), and by the transportation of hay (Schmidt and Pannell, 1996). Thus, weed resistance to herbicides can spread quickly once it has developed on one farm.

Van Deynze, Swinton, and Hennessy (2022) provide evidence that the spread of herbicide-resistant weeds is responsible for significant reductions in the use of conservation tillage in soybean production in the United States. Given the recent increase in public and private interest in tapping the potential of agricultural soils to sequester carbon as a strategy to mitigate climate change (Thompson et al., 2022), the forsaking of no-till might not only result in reduced short-term benefits to farmers and society but also eliminate benefits accumulated over previous years (Sawadgo and Plastina, 2022). It is only through permanent changes to soil management that permanent carbon sequestration can be achieved (Stevens, 2018). It should then be apparent that the challenges posed by herbicide-resistant weeds generate multiple externalities that include not only the spatial externality to neighboring farmers but also externalities to society as a whole. For example, the spread of herbicide-resistant weeds resulted in water quality and climate damages via fuel emissions valued at nearly $245 million (Van Deynze, Swinton, and Hennessy, 2022).

Hurley (2016) argues that successfully addressing the problem posed by herbicide-resistant weeds requires understanding both the pest biology and the socioeconomics aspects of pest management; complex, inflexible, and time-consuming practices are unlikely to be adopted by farmers without some incentive to do so. Along similar lines, Jussaume and Dentzman (2016) consider that the difficulties farmers face in adopting sustainable agriculture practices stem from a prevalent idea in U.S. farming that those practices should entail simplicity, ease, independence, and year-to-year decision making. Importantly, Hurley (2016) indicates that some farmers choose not to manage pesticide resistance because individual resistance management efforts will be futile unless neighbors are also managing it. Thus, the problem of weed susceptibility to herbicides can be argued to have characteristics of a public-good problem because it requires neighboring farmers to diversify their management actions (i.e., contributions), which may result in additional costs in the short term but would benefit all farmers in the landscape in the long term (Bagavathiannan et al., 2019).

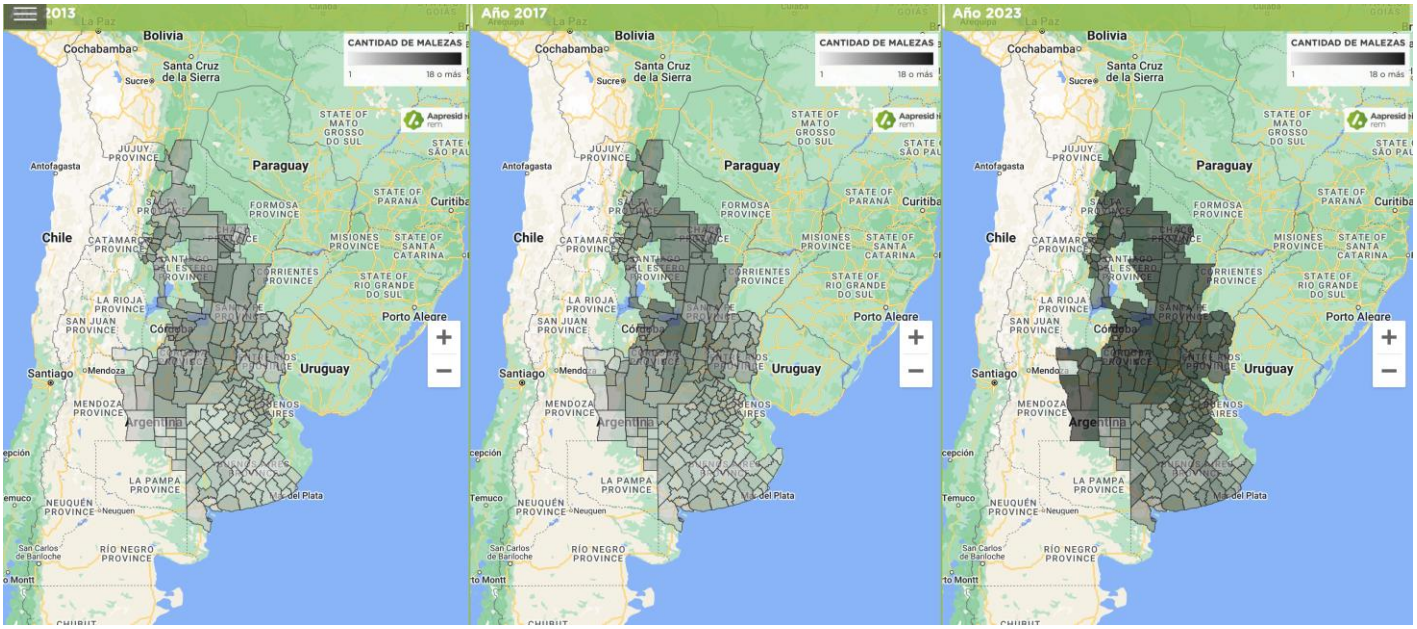
Whether a cooperative approach is necessary to curb resistance depends on the relative mobility of the pest involved (Miranowski and Carlson, 1986). Hence, effectively managing the regional challenge that herbicide-resistant weed populations pose would require farmers to implement integrated weed management on a community basis (Ervin and Jussaume, 2014). However, according to Jussaume and Dentzman (2016), the reluctance of U.S. farmers to adopt communal mitigating strategies to combat the spread of weed resistance is not due to a lack of knowledge about the existence of the problem or the possible tools that could be used to address it. Rather, the authors argue that what prevents U.S. farmers from acting cooperatively are two prevailing ideologies they hold: technological optimism and individualism. Based on farmers' responses gathered from a combination of focus group meetings and a self-reported farmer survey, Jussaume and Dentzman (2016) report that farmers expressed not only being aware of the presence of weeds on their farms—in fact, most of them (over 90%) stated that they were concerned about herbicide-resistant weeds—but they also indicated being aware of different recommendations for controlling weed resistance. However, the authors report that the majority, 59% of the respondents, indicated that the chances of a community-based action to adopt best management practices (BMPs) being effective would be either unlikely or neither unlikely nor likely (i.e., 50/50 chance).

Are the Challenges and Impacts of Herbicide-Resistant Weeds Unique to U.S. Farmers?

We gathered data from non-U.S. farmers to examine whether the spread and impact of herbicide-resistant weeds, as well as the response to such a challenge, are similar to those found domestically. In other words, we were interested in investigating whether the issues, attitudes, and behaviors observed in the United States are unique or reflect broader global farming trends. To this end, given the similar adoption rate of HT soybeans in the United States and Argentina and the comparable relative importance of the size of the soybean crop produced in the two countries, we collected data from Argentinean farmers.

Another major reason for focusing on Argentina is that no-till farming has been hugely popular among its producers. By greatly facilitating the sequestration of carbon in the soil, no-till is of paramount importance for the agricultural sector's efforts to successfully curb greenhouse gas emissions. The area grown under no-till in Argentina has been approximately 90% between crop years 2010/11 through 2021/22 (ReTAA, 2023). The percentage of adoption of no-till in the United States pales in comparison to that in Argentina; the top three soybean producing states, namely, Illinois, Iowa, and Minnesota, have no-till adoptions of 27%, 31%, and 5%, respectively; the state with the largest no-till adoption

Figure 1. Heatmap Depicting the Spread of Herbicide-Resistant Weeds in Argentina in 2013, 2017, and 2023



Source: AAPRESID (Asociación Argentina de Productores en Siembra Directa).

rate (57%) is Maryland, a relatively minor soybean producer (data from Sawadgo and Plastina, 2022).

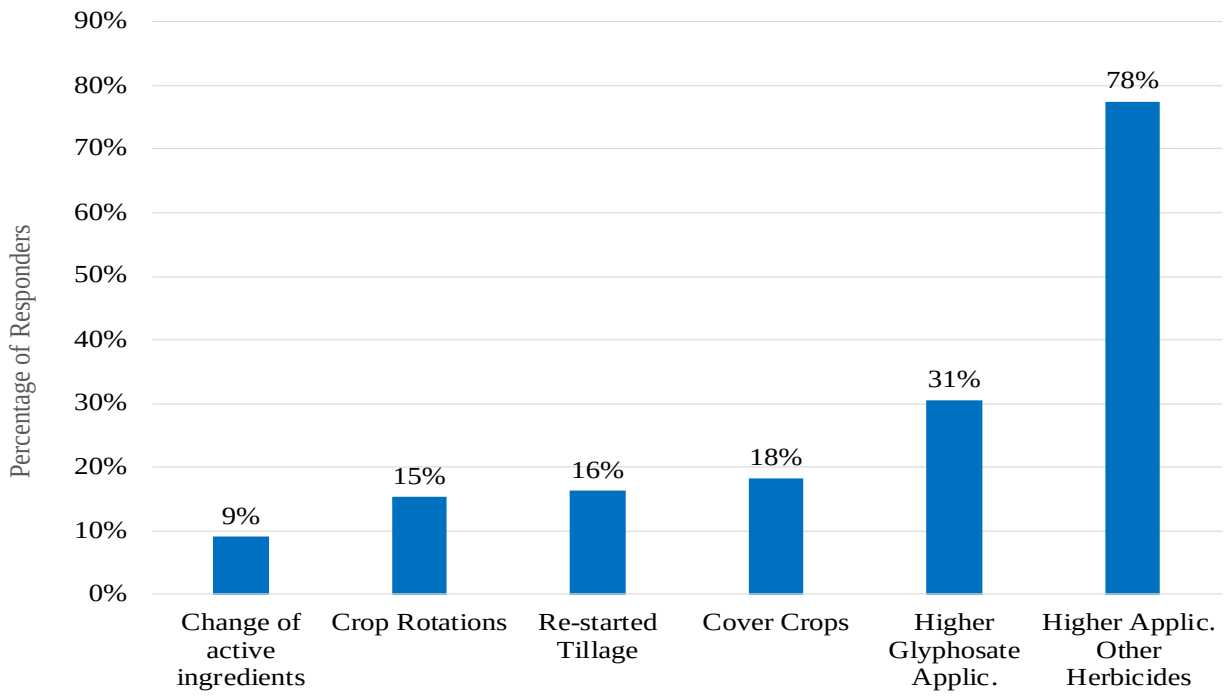
We collected our data in the spring of 2023 during two meetings organized by AAPRESID (Asociación Argentina de Productores en Siembra Directa, the "Argentinean Association of No-Till Farmers"). AAPRESID is a grassroots, non-profit, non-governmental grower organization well recognized within the agricultural community. AAPRESID promotes no-tillage farming as a way to foster sustainability in production based on soil conservation practices. Many researchers and agricultural experts attribute a significant portion of the widespread adoption of no-till practices in Argentina to the advocacy and support provided by AAPRESID. There is no national organization with similar characteristics and reach in the United States.

Combining the two meetings, we obtained a total of 98 responses. Those farmers managed over 1 million acres, 85% of which were located in the province of Buenos Aires. While the sample is not representative of the entire population of farmers in Argentina, we captured a high percentage of larger growers (approximately 23% of farmers that have between 25,000 and 50,000 acres and 39% of farmers with more than 50,000 acres). Thus, it could be argued that our sample is particularly informative regarding the characteristics and behavior of larger growers, who can be very influential and are likely industry leaders and trend-setters.

AAPRESID provides a mapping tool that tracks the aggregate spread of the different herbicide-resistant weed species throughout Argentina. Figure 1 depicts a three-panel heatmap of such a tool, from which it is clear that there has been a noticeable increase in the spread of the different herbicide-resistant weeds over the last decade. In our survey, we collected farm-level data regarding the spread of herbicide-resistant weeds. The farmers we surveyed reported that the average area in their operations affected by herbicide-resistant weeds increased by 12% from 2019/20 to 2021/22, reaching almost 50% in 2021/22. Thus, the experience of the farmers in our sample is consistent with the aggregate trend revealed by Figure 1 and denotes the magnitude of the problem.

Most individual farms we surveyed (54%) are dealing with four or more herbicide-resistant weeds. Given the magnitude of such a spread, it is not surprising that 65% of the farmers we surveyed self-reported being either quite concerned or very concerned regarding herbicide-resistant weeds in their area. The graph in Figure 2 provides information about the practices that farmers have adopted in response to the increasing pressure of herbicide-resistant weeds. The figure shows that 87% of the farmers, the largest percentage, increased the use of herbicides other than glyphosate; the result is obtained when combining the 78% of farmers that stated increasing the application of other herbicides along with the responses of 9% of the farmers that stated a change in the use of active ingredient. Such a response to glyphosate resistance by Argentinean farmers is similar to that of U.S. farmers, as reported by Perry et al. (2016)

Figure 2. Practices Adopted by Argentinean Farmers to Control Herbicide-Resistant Weeds



Notes: Total number of responses: 164 (some respondents reported more than one practice).
Source: Authors' collected data and calculations.

and Van Deynze, Swinton, and Hennessy (2022). The latter authors argue that by doing so, at least some farmers were able to continue applying conservation tillage.

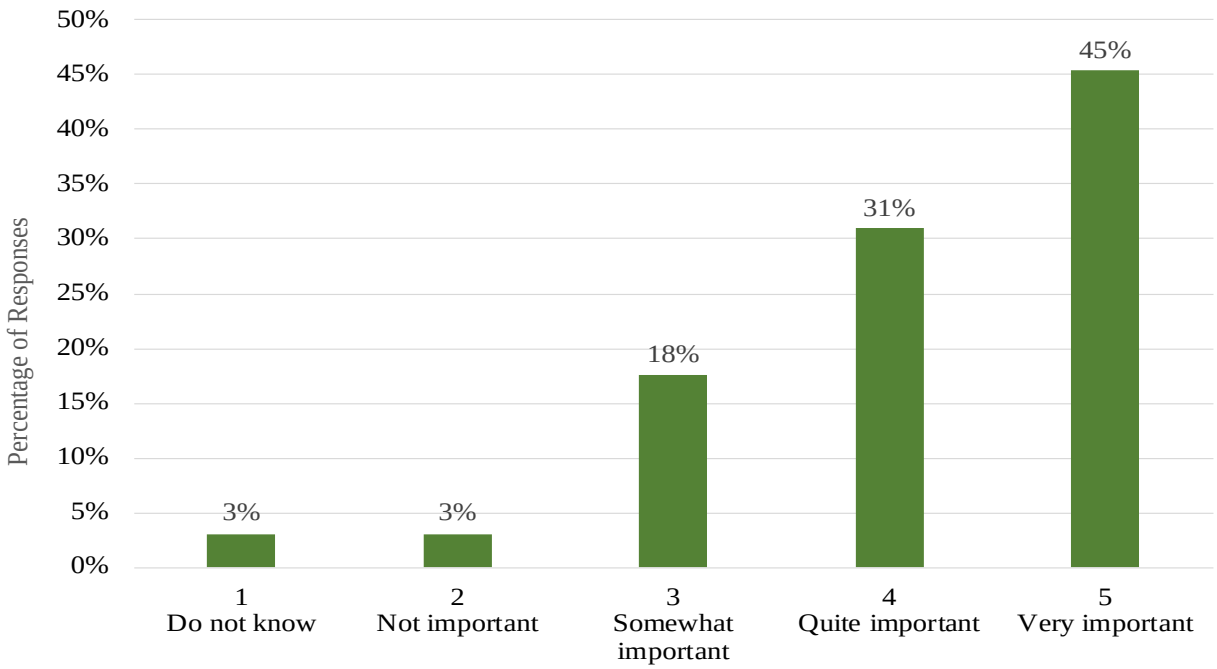
Figure 2 also shows that 31% of farmers reported the adoption of a higher application of glyphosate, making it the second most popular response to deal with herbicide-resistant weeds. This finding is in line with the argument made by Dover and Croft (1986), who contend that pesticide resistance typically promotes a further increase in the use of the chemical to offset the lower susceptibility of the pest, which, in turn, exacerbates the chemical resistance (along with all other externalities derived from the use of the chemical). Figure 2 illustrates that the third most adopted practice by Argentinean farmers to deal with herbicide-resistant weeds was to use cover crops. However, importantly, the graph also indicates that the fourth-largest percentage of farmers (16%) restarted tillage to control herbicide-resistant weeds. While such a finding is not surprising given the magnitude of the challenge herbicide-resistant weeds pose to Argentinean farmers, the result is particularly relevant when considering that the surveyed farmers were members of the organization AAPRESID that promotes no-till as a core value. Thus, it could be argued that the forsaking of no-tillage practices is very likely to be higher among the population of Argentinean farmers. Our survey findings are in agreement with those of Livingston et al. (2015), who report that U.S. corn and soybean farmers experiencing problems with herbicide-resistant weeds increased their use of glyphosate, started applying non-glyphosate herbicides, and restarted tillage practices. Similarly, Swinton and Van Deynze (2017) argue that the increasing challenge posed by herbicide-resistant weeds induces farmers to adopt additional herbicide applications, which carries an associated increase in human health risks derived from their use.

The Problem with Best Management Practices and the Potential for Collective Action

As the quantity of glyphosate-resistant weeds has increased, there is a growing body of research on proposed BMPs for controlling herbicide-resistant weeds (see, for example, Norsworthy et al., 2012). However, according to Bagavathiannan et al. (2019), current BMP standards, as well as research on how to enhance them, are a primary reason for the failure to effectively control weeds. The authors contend that BMPs overly concentrate on management choices at the property level and underestimate the cumulative effects of individual activities in determining outcomes at the landscape level, as well as the possibility of group practices that could enhance weed control. Likewise, Evans et al. (2018) find that farm-level weed management strategies are insufficient to hinder the spread of herbicide resistance.

While farmers have long organized cooperatively for marketing and promoting agricultural commodities, the

Figure 3. Importance That Argentinean Farmers Assign to Attempt Controlling Herbicide-Resistant Weeds Collectively with Their Neighbors



Notes: Total number of responses: 97.
Source: Authors' collected data and calculations.

adoption of collective action to address a common challenge that affects individual farms' production decisions remains elusive. The program to eradicate the cotton boll weevil in the United States is often cited as an example of a successful and highly coordinated area-wide pest management program (Ervin and Frisvold, 2016). But, in most cases, the implementation of area-wide pest management programs encounters resistance due to concerns over methods, free riding, general public opposition, and, importantly, uncertainty about stakeholder participation (Klassen, 2000). Even in Florida, where citrus greening disease presents a severe threat to the industry, collective action in terms of voluntary area-wide pest management efforts has failed, mainly due to strategic uncertainty concerns (Singerman and Useche, 2019).

Ervin and Frisvold (2016) sensibly point out that the approach of asking famers to adopt BMPs while providing them with technical assistance and industry subsidies has not worked well, favoring the notion that greater efforts should be made to support collective action. To get a sense of whether (and the extent to which) Argentinean farmers would agree with implementing a collective action for controlling herbicide-resistant weeds at the landscape level, we asked them such a question. Figure 3 reports that 76% of the farmers we surveyed considered it either quite important or very important to do so. In fact, when asked whether they were willing to coordinate actions with their neighbors to control herbicide-resistant weeds, the vast majority of the farmers in our sample (95%) responded "yes." This denotes a significant difference relative to U.S. farmers in their perception regarding the effectiveness of collective action.

In the survey, we also asked farmers how concerned they would be regarding different potential barriers to coordinating actions among neighboring farmers to control herbicide-resistant weeds using a Likert scale ranging from 1 to 5, where 1 = "No concern," 3 = "Somewhat concerned," and 5 = "Very concerned." The set of potential barriers consisted of (a) trusting that others would coordinate, (b) the effort needed to coordinate actions, (c) the cost required to coordinate actions, (d) depending on others to obtain a benefit, and (e) program implementation. Table 1 reports Argentinean farmers' level of concern for the different barriers and shows that 61% of the respondents are either quite or very concerned about two barriers: trusting that others would coordinate and depending on others to obtain a benefit. These results denote that issues related to strategic uncertainty are their top concern, and are similar to those reported by Singerman, Lence and Useche (2017), who find that the top stated reason by both participants and non-participants in a voluntary area-wide pest management program to combat citrus greening disease in Florida was their belief that others did not coordinate; in fact, strategic uncertainty was found to be a major determinant behind the failure of such collective action efforts (Singerman and Useche, 2019; Lence and Singerman, 2023).

Table 1. Argentinean Farmers Self-Assessed Potential Barriers to Coordinate Actions among Neighboring Farmers to Control Herbicide-Resistant Weeds

	Not Concerned 1	2	Somewhat Concerned 3	4	Very Concerned 5
Trusting that others would coordinate	6%	7%	26%	30%	31%
Effort needed to coordinate actions	8%	8%	29%	25%	31%
Cost required to coordinate actions	18%	20%	27%	15%	20%
Depending on others to obtain a benefit	7%	10%	23%	21%	40%
Program implementation	7%	11%	23%	27%	32%

Notes: The number of responses were 91 for all barriers listed except for "Trusting that others would coordinate," which got 89 responses.
Source: Authors' collected data and calculations.

Conclusions and Policy Implications

We find evidence that the challenges and impacts facing U.S. farmers from herbicide-resistant weeds are not unique. Argentinean farmers not only face similar issues but also responded to the problem by adopting similar practices to those used by U.S. farmers. Herbicide-resistant weeds present a problem that may be best addressed through collective action, but the strategic uncertainty involved—especially if the effort it entails is voluntary—undermines the trust necessary for the action to succeed. The primary challenge is that farmers' rewards are dependent on other farmers' behaviors in addition to their own, which is also the source of strategic risk. Contributing to the provision of a public good involves strategic risk because a critical mass of participants is required to achieve success; if this mass is not reached, the public good will not be delivered and the rewards for those who contributed will be smaller. Given the near unanimous willingness to coordinate actions with their neighbors stated by Argentinean farmers, we find evidence that their perception regarding the effectiveness of collective action to tackle herbicide-resistant weeds is more positive relative to that of U.S. farmers (obtained by Jussaume and Dentzman, 2016).

In situations where coordination is crucial, public signals have a role in coordinating outcomes that goes beyond such signals' informational content because public information can transmit strategic knowledge about other people's beliefs (Morris and Shin, 2006). Incorporating public research and extension, along with suitable incentives, into efforts to promote collective action could potentially enhance trust and mitigate the negative impact of strategic uncertainty. The "coordination frontier", a tool recently introduced by Lence and Singerman (2023), can be useful to examine the circumstances in which varying degrees of voluntary coordination can be successful; it can also be used to determine the size of the financial incentives required to make it so. Thus, the "coordination frontier" can help reduce concerns about strategic uncertainty and encourage collective action. Moreover, extension can play a crucial role in lowering strategic uncertainty and promoting collective action because (a) discussion among players fosters cooperation (Orbell, van de Kragt, and Dawes, 1988); (b) cooperation is reciprocated; and (c) cooperation increases with the return on investment in the public good (Dawes and Thaler, 1988). In fact, there is evidence that extension promotes communication and collaboration among growers in pest management (Stallman and James, 2015).

A nontrivial challenge to implementing collective action to deal with herbicide-resistant weeds may be land tenure. Some studies sensibly argue that the incentive for land renters is to focus on short-term profits, making them less likely to adopt actions for which they are unlikely to reap any benefits, including herbicide resistant management (Norsworthy et al., 2012; Owen et al., 2015; Rubione and Ward, 2016; Shaw, 2016). This could represent an important potential barrier to successful collective action. However, using national-level data for corn and soybeans in the U.S. from 2010 to 2012, Frisvold et al. (2020) found no statistically significant differences in herbicide use or weed management practices between rented and owned land. But the authors note that there is evidence indicating that growers now possess greater experience with herbicide-resistant management and are more concerned about weed resistance to herbicides. Thus, even if land tenure posed a barrier to implementing collective action, a potential solution to such a hurdle could be to provide renters with a subsidy to follow through with collective action practices.

An alternative solution to the challenges posed by herbicide-resistant weeds is technological innovation. Some companies are already selling an artificial intelligence tool that can be pulled behind a tractor and be used to identify and remove weeds using lasers. Such a technology will likely require a significant initial

investment, which would eventually translate into chemical savings and, importantly, reduce the externalities associated with their use. However, it is doubtful that such a development will be adopted in most countries as promptly and widely as it may in the United States. Farmers in places like Argentina, where there is little access to credit or credit is available but at a prohibitive rate, are unlikely to adopt such a technology on a widespread basis in the near future.

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