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Herbicide Resistance: Economic and Environmental Challenges

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This article presents comparative perspectives from Australia, the European Union, and the United States from a plenary session, "Herbicide resistance: Challenges for Farmers and Implications for the Environment" at the 19th Annual Conference of the International Consortium on Applied Bioeconomy Research. Herbicide-resistant (HR) weeds threaten the sustainability of herbicide-tolerant (HT) crops, pose environmental risks from alternative weed control methods, and are altering public and private research and development programs. Institutional responses to HR weeds across the three regions, while confronting similar problems (in some respects, but not others), are taking different forms. The article discusses public policies and private-sector strategies to address weed resistance problems. Considerations of HR weeds are already transforming regulatory approval processes for new HT crop varieties. We conclude by discussing over-arching public policy and agricultural research challenges.

Key words: Australia, biotechnology, economics, European Union, herbicide-resistant crops, herbicide-resistant weeds, integrated weed management, regulation, United States, weed seed control.

Herbicide Resistance: Economic and Environmental Challenges

Herbicide-resistant (HR) weeds threaten the sustainability of herbicide-tolerant (HT) crops, pose environmental risks from increased use of alternative weed-control treatments, alter public and private research and development (R&D) programs, and necessitate new approaches to manage such resistance. This article presents comparative perspectives from Australia, the European Union (EU), and the United States on HR weed problems and policy responses to them. HR weeds have evolved in distinct agronomic and institutional settings across these three regions. This means that institutional responses to HR weeds, while confronting similar problems (in some respects, but not others) are taking different forms across the regions. The article discusses recent public policies and private-sector strategies to address current weed resistance problems. Considerations of HR weeds are already transforming regulatory approval processes and deployment of new HT crop varieties. There will likely be greater linkages between how current biotechnologies are managed and how and whether new ones will be developed and approved. We conclude by discussing over-arching public policy and agricultural research challenges.

Herbicide Resistance in Australia

Starting in the late 1980s, herbicide resistance emerged as a major influence on Australian crop systems (Howat, 1987; Powles & Holtum, 1990). For more than 20 years, Australia stood out as having by far the most serious case of herbicide resistance in the world. The primary reason for this was the widespread occurrence of annual ryegrass (*Lolium rigidum*). This major weed of Australian crops possessed a remarkable ability to rapidly evolve resistance to multiple selective herbicides without suffering any fitness penalty. Herbicides that had become central to farmers' cropping systems (such as diclofop methyl and chlorsulfuron) were lost completely to most farmers. Now, in major cropping areas, close to 100% of field samples of ryegrass plants are found to have resistance to selective herbicides and most are resistant to multiple herbicide modes of action (Owen, Martinez, & Powles, 2014a). Subsequently, herbicide resistance has been identified in populations of various other weeds, including wild radish (*Raphanus raphanistrum*; Walsh, Duane, & Powles, 2001) and wild oats (*Avena fatua*; Ahmad-Hamdani, Owen, Yu, & Powles, 2012).

As a result of the explosion of herbicide resistance in the 1990s and 2000s, grain farmers were forced to innovate. With help from weed scientists, they explored a range of weed control practices to replace the lost herbicides. These included tactical use of heavy grazing by livestock, increasing crop seeding rates to increase competition with weeds, a variety of methods to destroy weed seeds before they entered the seed bank, and alternative herbicides.

Other important changes in the dominant farming system were also occurring at about this time. Farmers increasingly moved from rotating crops with pastures (used for livestock grazing) to continuous-crop rotations involving cereals, legume crops, and canola. Part of the motivation was to avoid the carry-over of weed seeds from pastures into crops. However, the loss of grazing pressure on weeds reduced the diversity of weed control methods being used, adding to the selection pressure for resistance to key herbicides.

Adoption of zero tillage increased rapidly, reaching more than 90% of farmers in the main crop-growing areas (Llewellyn, D'Emden, & Kuehne, 2012). This provided major financial benefits through earlier sowing and an ability to sow with less rain, as well as reducing soil erosion. However, it increased reliance on herbicides at a time when key herbicides were being lost to resistance.

Few farmers adopted novel weed control practices in order to avoid or delay the onset of resistance to selective herbicides. However, once resistance occurred, they all changed their practices. To the extent that it was possible, farmers attempted to move to new selective herbicides following the loss of their preferred herbicides. However, this strategy had a limited life, as ryegrass was able to rapidly develop resistance to the new selective herbicides that were used. It was essential, sooner or later, to incorporate non-chemical weed control methods as a major component of the farming system.

Few farmers chose to revert to a cultivation-based farming system. The benefits of zero tillage in the Australian environment are too great to make a return to cultivation attractive. Instead, farmers have increasingly focused on new methods to capture and destroy weed seeds at harvest time. Various systems have been developed, including the following.

- *Burning of narrow windrows.* Crop residues leaving the harvester are concentrated into narrow strips, which are subsequently burned to destroy weed seeds.
- *Chaff onto tramlines.* Many farmers practice tramline farming, where seeding, spraying, and harvesting machinery all follow the same tracks, to confine soil compaction. They are able to direct chaff (including weed seeds) leaving the harvester onto those tracks, where they are destroyed by machinery tires.
- *Chaff carts*. A cart is towed behind the harvester, into which chaff is directed. It is subsequently dumped and burned, or removed from the field and used for grazing.
- *Harrington Seed Destructor.* Chaff is directed into the seed destructor, which is towed behind the harvester (Walsh, Harrington, & Powles, 2012). The chaff is milled, destroying almost all weed seeds.

Field surveys have found that the density of weed seeds in fields is no higher where resistance is present than where it is not (Llewellyn, D'Emden, Owen, & Powles, 2009). In other words, rather than tolerating higher weed numbers in the absence of the most efficient weed control methods, farmers are switching to alternative methods that provide a similar level of control. Even though these alternative methods are somewhat more expensive, the additional cost is worth bearing in order to contain weed numbers.

The enormous challenges that farmers have had to overcome with resistance to selective herbicides has left them very conscious of herbicide resistance as an issue. Crop farmers are well aware of herbicide resistance (Llewellyn, Lindner, Pannell, & Powles, 2002, 2004), and almost all of them have had to change their management in order to deal with it.

Market and Policy Responses

As well as the changes made by farmers in response to herbicide resistance, there were also responses amongst herbicide suppliers, machinery manufacturers, scientists, and policymakers. From an early stage, weed scientists advocated for herbicides to be identified by their mode of action (MoA), rather than solely by their name, in order to make it easier for farmers to combine or rotate herbicides of different types. A system was adopted by the industry in the early 1990s. The system was regulated as a requirement for herbicide labels and farmers soon learned of the importance of the MoA group for each herbicide they used.

Companies have developed new machinery of various types. Notable examples are the chaff carts used to catch weed seeds behind a harvester, and the Harrington Seed Destructor, which not only catches seeds but also destroys them.

The release of Roundup Ready (RR) crops is regulated by the Office of Gene Technology Regulator. Currently, the only RR crop available to grain farmers is canola. While RR canola has improved farmers' profits (Monjardino, Pannell, & Powles, 2005), limiting the RR gene to a single crop is helping to limit the usage of glyphosate, ensuring that the evolution of glyphosate resistance is slower than it has been in the United States. If additional RR crops are brought to the regulator, the risk of resistance will be one of the factors that is considered. Leading weed scientists will strongly oppose the release of additional RR crops and, given their experience with resistance, many farmers would be broadly supportive of this position.

Economics of Herbicide Resistance in Australia

The bio-economics of herbicide resistance have been intensively studied in Australia for more than 20 years. Numerous studies on many different aspects of the problem have been conducted and have influenced thinking within the industry and amongst scientists and extension agents. A key insight, obtained from weed population models that represent the genetics of herbicide resistance, is that the only way to avoid herbicide resistance indefinitely is to drive resistance genes to extinction within a field or farm (Neve, Diggle, Smith, & Powles, 2003a, 2003b). This requires following any usage of an herbicide with additional contrasting control methods that kill all, or very nearly all, of the weeds that survived the herbicide. This process must be commenced soon after the commencement of herbicide usage so that the density of resistance genes is still low enough for extinction to be feasible.

From these insights, it is clear that most strategies recommended to prevent herbicide resistance will not avoid it indefinitely because they do not kill all, or nearly all, survivors. Where resistance is conferred by a single gene (as is the case in most Australian examples), rotating between herbicides with different MoAs extends the life of an herbicide by reducing its frequency of use. In most cases, the total number of applications is not increased—the applications are simply spread out over a longer time period. Mixtures of herbicides help to reduce weed numbers, but they do not prevent herbicide resistance development unless they are able to drive genes to local extinction.

Without gene extinction, bio-economic modelling has shown that taking costly pre-emptive action to delay the onset of herbicide resistance is not the economically optimal strategy (e.g., Pannell & Zilberman, 2001; Powles, Monjardino, Llewellyn, & Pannell, 2001). Rather, the superior strategy is to use the available herbicide applications to push the weed population to very low numbers so that when resistance does emerge, it is easier for alternative control methods to contain the population. Lower densities are easier to manage because they are more susceptible to competitive pressure from the crop. For this strategy to work, farmers must monitor the resistance status of their weeds so that when resistance does emerge, they are ready to switch rapidly to alternative control methods. It is also important that herbicides are used effectively to drive weed numbers to low levels. Otherwise the farmer may have to deal with high weed densities just at the time when resistance emerges.

Where extinction is possible, the economics of pre-emptive action are different. Weersink, Llewellyn, and Pannell (2005) showed that the “double knock” strategy modelled by Neve et al. (2003a, 2003b) can be an economically viable way to permanently prevent resistance. Whether its benefits exceed its costs depends on two main factors—the time frame until resistance is expected to occur in the absence of the preventative strategy and the expected increase in weed control costs after resistance occurs. The shorter the time until resistance onset, and the greater the cost increase following resistance, the more likely it is that preemptive action to prevent resistance will be profitable.

Once resistance does occur in a field, the economics of alternative farming systems can be dramatically affected. In general, the net benefits of adopting alternative weed control methods improve (Abadi, Pannell, & Gorddard, 1993; Bathgate, Schmidt, & Pannell, 1993; Doole & Pannell, 2008; Doole, Pannell, & Revell, 2009; Gorddard, Pannell, & Hertzler, 1995, 1996; Monjardino, Pannell, & Powles, 2004a, 2004b; Schmidt & Pannell, 1996a). Which practices become the most attractive is highly case specific, depending on local conditions, the existing farming system, and which practices are still available.

The observation noted earlier that weed numbers do not increase significantly in fields where herbicide resistance is present is explained by economic analysis of the changing optimal strategy following resistance onset. Pannell and Zilberman (2001) showed that it is optimal for the farmer to bear increasing costs of weed control in order to keep the weed density very low.

Economists are interested in the occurrence of market failure to justify a policy response to any particular issue (Pannell, 1994). Phenomena that involve spread of biological agents are often associated with market failure, and this is relevant to the spread of HR weeds (Marsh, Llewellyn, & Pannell, 2006). However, in the case of ryegrass resistance to selective herbicides in Australia, the external cost of resistance spread has been minor in most cases. The reason is that almost all farmers were using similar herbicides intensively, so they were evolving resistance on their farms at approximately the same rate. Spread of resistant weeds from one farm to another is a minor issue if the second farm was on the verge of generating a resistant weed population internally anyway. It appears likely that the speed of development of glyphosate resistance will be more variable amongst farms. If so, the potential for external costs from weed spread will be greater.

A second potential cause of market failure is where the onset of resistance leads to the adoption of weed control practices that generate external costs. A concern in the United States has been the re-adoption of cultivation-based farming systems following the loss of glyphosate to resistance over large areas (Culpepper, Owen, Price, & Wilson, 2012; Price et al., 2011). For example, a number of studies have found that adoption of herbicide-tolerant crops is positively associated with the adoption of conservation tillage methods (Fernandez-Cornejo, Hallahan, Nehring, Wechsler, & Grube, 2012; Frisvold, Boor, & Reeves, 2009; Kalaitzandonakes & Suntornpithug, 2003; Roberts, English, Gao, & Larson, 2006). However, at least in Australian conditions, dis-adoption of zero tillage has not occurred so far, and it appears unlikely to do so in the future. Rather, it is expected that farmers will increasingly adopt novel weed control methods, particularly methods for destruction of weed seeds at harvest.

Thirdly, market failure can arise due to information failures. Research and extension have contributed greatly to reducing costs to farmers from herbicide resistance. For example, the model (Lacoste & Powles, 2014; Monjardino et al., 2003; Pannell et al., 2004) has helped to educate thousands of farmers about the economics of alternative weed control practices that may be adopted following the onset of herbicide resistance. The evaluation of alternative farming systems can be extremely complex, especially where systems have influences on multiple resource management issues (e.g., herbicide resistance and soil salinity; Doole et al., 2009), or where there are interactions between control methods (Schmidt & Pannell, 1996b). RIM helps farmers and scientists to understand these complexities. The use of RIM in training workshops has been shown to be effective in influencing farmers' perceptions of the resistance problem and its management and their intentions to adopt alternative practices (Llewellyn & Pannell, 2009). The RIM model has subsequently been adapted for the Philippines (Beltran, Pannell, Doole, & White, 2012a; Beltran, Pannell, & Doole, 2012b) and South Africa, and the Australian version has been used in teaching and training in various countries.

The Future: Prospects, Challenges, and Research Questions

There will never be a silver-bullet solution to herbicide resistance. Technologies such as the Harrington Seed Destructor are likely to become cheaper and even more effective as their market grows and there is further innovation, but they will never provide a complete solution because of the capacity of weeds to evolve resistance to any effective control mechanism that is used repeatedly. Effective ongoing weed control will always require a mixture of weed control methods used in combination (Powles, 2008).

Resistance to selective herbicides has not proven to be as severe a threat to agricultural profitability in Australia as was once feared. Farmers with weeds that have severe resistance to multiple herbicides are continuing to grow crops profitably, thanks to diversification of weed control methods, supported by innovation.

In the analysis of a survey conducted in 2000, we found that some farmers were optimistic about the likelihood of new herbicides with novel MoAs being developed to replace those lost to herbicide resistance (Llewellyn et al., 2002, 2007). The more optimistic they were about this, the less likely they were to adopt a diverse package of weed control methods (Integrated Weed Management). Although no public information is released by herbicide companies to indicate prospects for new herbicide MoAs in the future, we can observe that it has now been more than 20 years since the last new herbicide type was released. It would seem inadvisable for farmers to rely on an endless stream of new herbicides becoming available. Indeed, Australian farmers have moved beyond that reliance, by necessity.

Another novel technology with potential for herbicide resistance is precision herbicide application. While this is unlikely to ever be viable within a growing crop (Bennett & Pannell, 1998; Pannell & Bennett, 1999), it may help to reduce the frequency of herbicide application in out-of-crop weed control (e.g., control of summer weeds in southern Australia). This would contribute to extend the life of the relevant herbicides, particularly glyphosate.

An outstanding challenge that remains to be faced in Australia is widespread resistance to glyphosate. With the RR gene present in a minority of grain crops (only canola), and with farmers highly aware of resistance through their experiences with selective herbicides, the development of glyphosate resistance is likely to be much slower than has occurred in the United States. Nevertheless, it seems likely that it will eventually become widespread. Although farmers have generally coped well with the loss of most selective herbicides—with only modest reductions in profit due to resistance—resistance to glyphosate would inevitably impose additional costs on farmers (Jacobs & Kingwell, 2016). The loss of glyphosate would further improve the economics of weed-seed control at harvest, such as by the Harrington Seed Destructor. Jacobs and Kingwell (2016) found that, without harvest weed-seed control, and given a high initial weed seed density, resistance to glyphosate would reduce farm profit in Western Australia by roughly 37%; with harvest weed-seed control, the reduction in profit due to glyphosate resistance would be only around 13%. This would be a sufficient benefit to make the Harrington Seed Destructor a highly profitable investment.

Research on the economics of herbicide resistance in Australia has been quite comprehensive. Remaining roles for economics in Australia (apart from communicating established insights) include evaluating new technologies and systems as they emerge as options; understanding how optimal weed control strategies change in response to other changes in markets, climate, or the farming system; helping to place new scientific knowledge in a management context; and advising policymakers, particularly in relation to glyphosate resistance.

Herbicide resistance is a complex, multi-faceted issue. Analysis to support management and policy decisions needs to be founded on good understanding of the biology, economics, and farming systems. Modeling in Australia that integrates these three facets has yielded a number of important insights. Most techniques suggested to prevent herbicide resistance in reality only offer a delay in its onset. Genuine prevention requires local extinction of herbicide resistance genes. In the absence of likely gene extinction, the economics of taking costly measures to delay herbicide resistance are not compelling, which may explain the observation that most Australian farmers did not change their management in response to resistance to selective herbicides until they were forced to by the actual onset of resistance. Now they have adopted innovative non-herbicide weed control methods and are able to continue farming profitably.

The European Case

The European Union (EU) has slightly more than 100 million hectares of arable land, about half that of North America. However, there is a huge difference in the average size of agricultural holdings. US farms are about twelve times larger than their European counterparts (roughly 180 ha vs. 14 ha in the European Union, per data for 2010). Australia's grain farms are much larger again, averaging thousands of hectares in the main grain-growing regions. This fact has important implications for weed control. While North American and Australian farmers are looking for flexible, efficient weed control strategies, European farmers may be less time constrained. Moreover, weed control strategies also differ because of regulations: authorized herbicides and usage are different, and genetically modified herbicide-tolerant (GMHT) crops are not authorized in the EU. Despite these differences, European farmers are also facing weed resistance issues since the first case was identified in 1973. However, patterns of herbicide resistance and the challenges they pose to farmers are specific to European agriculture.

Regulation and Herbicide Use in the EU

In the EU—notably in its Western part—weed control in cereal production relies extensively on herbicide use. However, the use of herbicide is subject to strict legislation. In addition to the REACH Regulation (Reg. EC 1907/2006) that applies to all chemicals, plant protection products have to undergo an extensive risk assessment under a specific regulation. Only products that successfully passed this risk assessment are placed on a positive list of products that can be used in the EU for plant protection. Moreover, there are other pieces of legislation that can also impact the use of herbicides: the regulation on residues in food and feed sets up minimum residue levels (MRLs) for pesticides. Under the Water Framework Directive and Drinking Water Directive, restrictions on herbicide use can be enforced when surface or groundwater quality is not satisfactory.

On top of the European legislation, national regulators can also impose other restrictions on herbicide usage. Altogether, this has led to a reduction—rather important in some EU Member States—of the number of herbicide preparations available to farmers. For instance, in France, the balance between the number of new authorized herbicides and withdrawals is negative since the mid-2000s (Figure 1). One reason for this is because no new herbicide MoA has been released in the last 20 years. In fact, the situation is even more concerning when looking at the herbicides available for weed control for a given crop. Each MoA group of herbicides includes a number of herbicides with different active ingredients (AIs). In many cases, the number of AIs that fall within a MoA group is very small, sometimes only

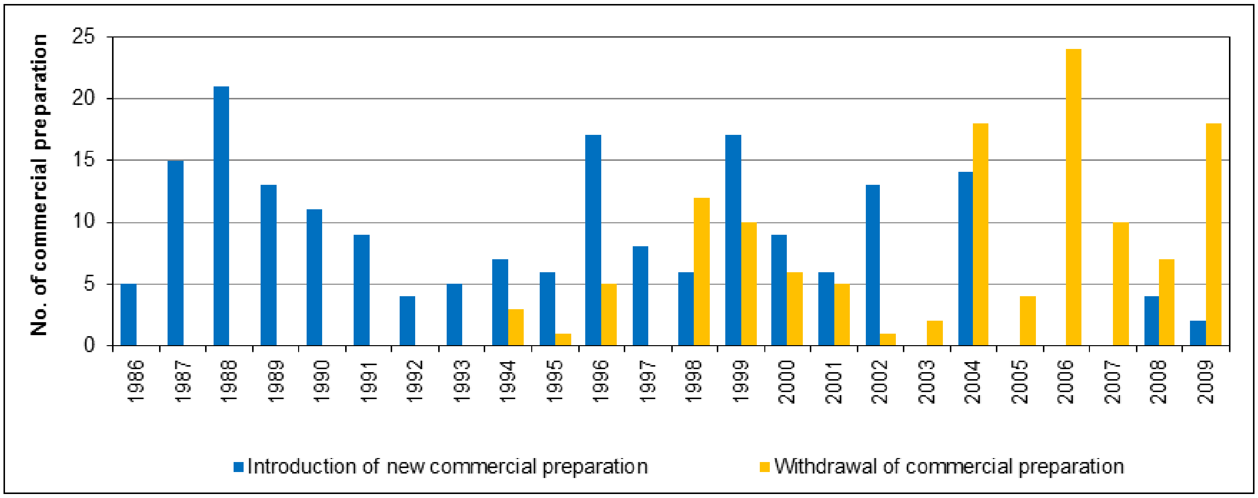

Figure 1. Balance of herbicide preparation available for weed control in France, 1986-2009.
Source: Nicola and Schott (2009)

one. For example, in France there are 10 different MoA groups relevant to weed control in canola, but for six of those groups, there is only a single AI available for use (a different one in each case). In those six cases, withdrawal of a single herbicide from the market would see an entire MoA group lost for canola. The situation is similar, although less acute, for the other major crops such as wheat, maize, and sunflower (Gasquez, 2015). In sum, the reduction in available AIs drives farmers to reduce the diversity of AIs and MoAs that they use on their fields, which in the end also reduces the diversity of the selective pressure applied on the weed populations.

Figure 2 illustrates the situation described above for weed control in cereal fields in another Western European region, Great Britain. Chemical weed control is becoming highly reliant on one single class of herbicide (the sulfonylureas), which have progressively replaced all other families of herbicides, such as the urea derivatives or triazines. This overreliance has also been observed in France, where a farmer survey has shown that more than half of the herbicide commercial formulations used for weed control in wheat fields in one single treatment contained at least one sulfonylurea AI (Gasquez, Fried, Délos, Gauvrit, & Reboud, 2008). Another survey conducted in 2011 has shown that one single AI—Iodosulfuron-methyl-sodium, a sulfonylurea—had been used on about 55% of wheat fields in France (Ministry of Agriculture, Agri-Food, & Forestry, 2011). The same survey also confirmed the tendency to rely on fewer MoAs for weed control in wheat.

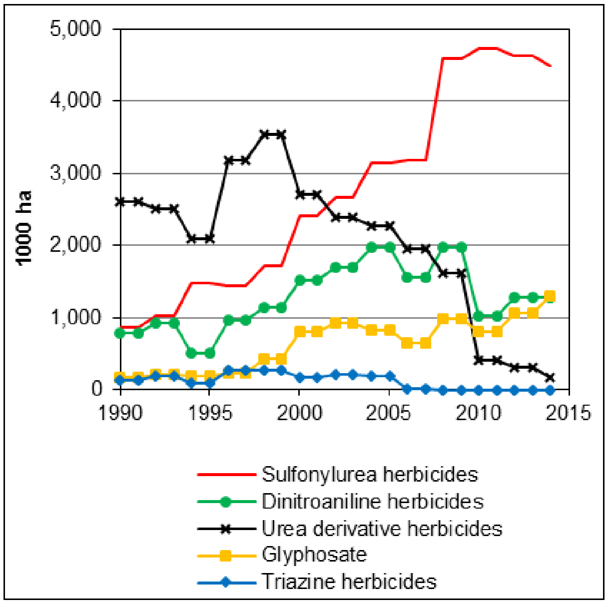

Figure 2. Total area treated for weed control in cereals by class of herbicide in Great Britain, 1990-2014.
Source: Pesticide Usage Surveys (Food and Environment Research Agency [FERA], 2015).

Cultivation of Herbicide-tolerant Crops in the EU

While they are extensively used in other parts of the world—notably the Americas and Australia—GMHT crops are not part of the toolbox of EU farmers for weed control since they are not authorized for cultivation. However, herbicide-tolerant (HT) crops, obtained from non-GM techniques such as mutagenesis or conventional breeding, are authorized in the EU and some varieties are actually cultivated. This is notably the case of three imidazolinone (IMI)-tolerant varieties—a sunflower introduced on the EU market in 2004, a rice introduced in 2006, and an oilseed rape introduced in 2010, all commercialized under the brand Clearfield®. In addition, another sunflower tolerant to tribenuron was commercialized in 2007 with the name Express Sunflower®. Note that both imidazolinone and tribenuron belong to the same herbicide class of sulfonylurea. There are no official data about the actual use of these non-GM HT varieties by EU farmers, but their cultivation appears to be very significant. The IMI-tolerant rice is estimated to be cultivated on approximately one-fourth of the total rice area of the five EU countries where it is commercialized, while the market share of the IMI-tolerant sunflower is reported to be around 45% for 12 EU Member States (Kudsk, 2014).

Herbicide Resistance in the European Union

The first case of herbicide resistance in the EU was detected in Austria in 1973 and corresponds to an *Amaranthus retroflexus* resistant to triazine that was collected in a maize field. Since then, about 70 different weed species resistant to different classes of herbicides have been identified in the EU (Heap, 2015). The number of unique cases (UC) of resistance (one species, one site of action) is even higher since one single species can be resistant to various herbicides. The International Survey of Herbicide-Resistant Weeds (Heap, 2015) gathers all the information about identified UC of resistance. According to its records, France (44 UC for 36 different species), Italy (42 UC for 21 different species), Germany (41 UC for 22 different species) and Spain (34 UC for 26 different species) are the countries where the issue is the most acute (Figure 3).

Data from the International Survey also allows one to represent of the evolution of weed resistance over time. Figure 4 depicts the onset of UC of weed resistance in the EU by type of herbicide MoA. During the 1990s, the overwhelming majority of new UC were due to the photosystem II (PSII) inhibitors, i.e., triazines, the family of atrazine. Since the beginning of the 2000s, we note the growing number of UC due to acetolactate synthase (ALS) inhibitors, the family that includes sulfonylurea herbicides. In sum, this reflects the pattern of herbicide use in the EU, although some herbicide MoAs are more likely to evolve resistance. Glyphosate that is generally associated with a moderate risk of resistance evolution has indeed generated few UC of resistance in the EU, compared to the extent of its use. In this aspect, the situation in Europe diverges notably from what is observed in the United States.

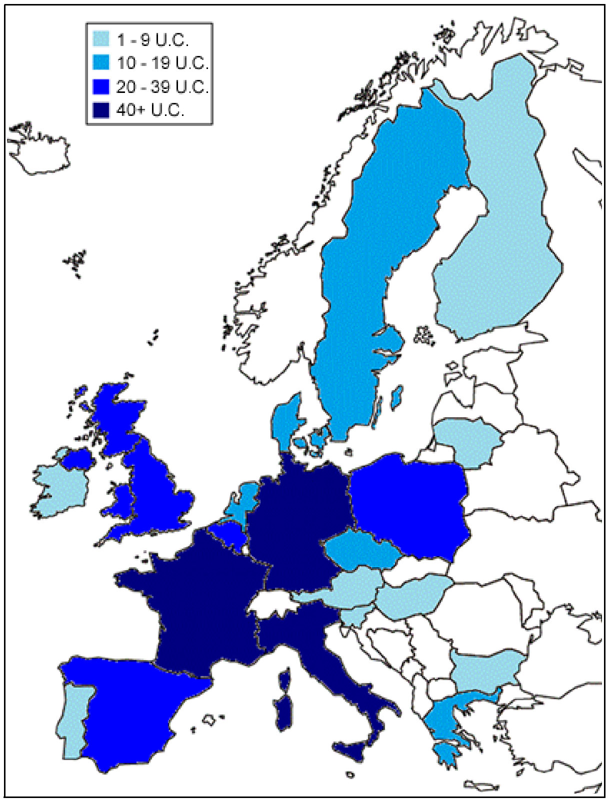

Figure 3. Unique cases of resistant weeds in EU Member States (map).

Source: Heap (2015)

Looking at the UC for each of the major crops individually shows different situations. There are numerous HR weeds that can affect maize; however, most of them were identified in the 1980s when atrazine was extensively used. For instance, out of the 18 UC identified in maize weeds in France, 17 are due to atrazine and were reported before 1989. In fact, since the use of atrazine has been banned in the EU, there are currently no big issues of weed resistance in maize fields. The situation is different for wheat. There was a first boom of weed resistance at the beginning of the 1990s, mostly due to Acetyl CoA Carboxylase (ACCase) inhibitors, a family of herbicide used to control grass weeds in broadleaf crops. Then only a few new UC of resistance were observed until the mid-2000s, when a second wave of resistance uptake was reported, this time due to ALS inhibitors. The UC of weed resistance also appeared in two waves in orchard production. The first one was reported in the 1980s and was due to triazine herbicides, mainly in the Northern and Continental parts of the EU. Then, an important surge of UC started in 2005 and

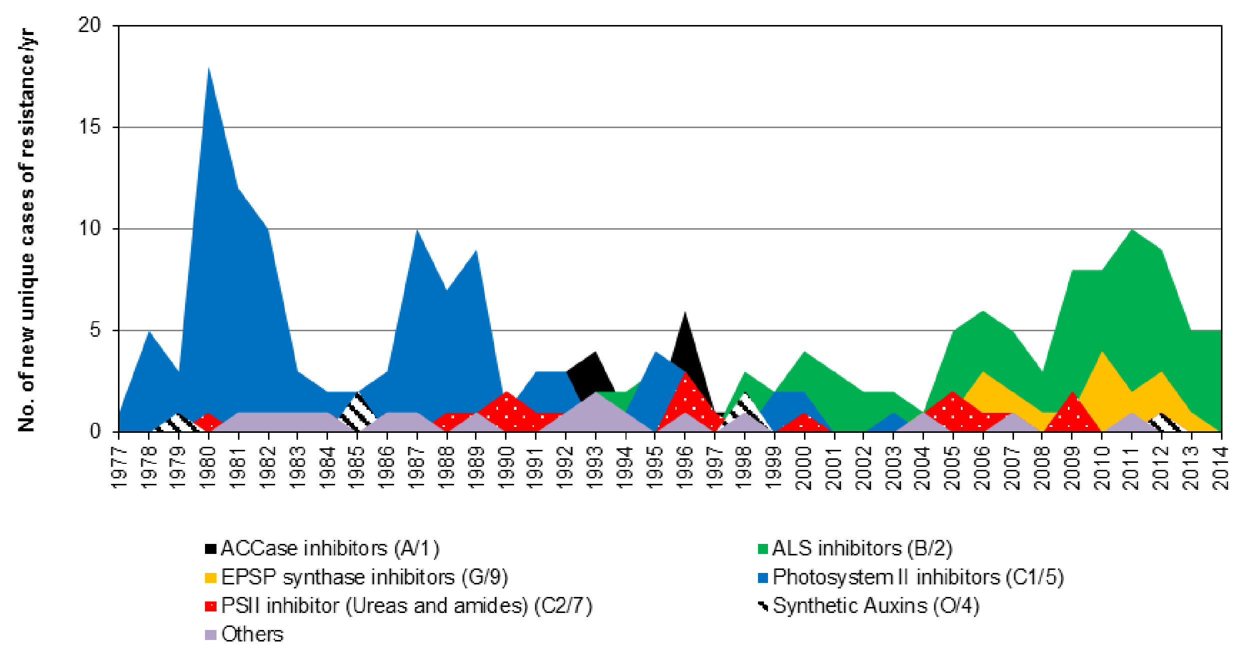

Figure 4. New unique cases of weed resistance in the EU Member States, 1977-2014.

Source: Author calculations based on data from Heap (2015)

affected mainly the Mediterranean countries. It is mostly due to glyphosate, which has been persistently used in these regions to control weeds in orchards in place of triazine herbicides (Powles, 2008). The last interesting case is rice. Most UC reported to affect rice production have been identified in Italy (12 UC out of 15 in total in the EU). They are due to both ALS inhibitors and PSII inhibitors (propanyl). One characteristic of the rice production in Italy is that it is cultivated with almost no crop rotation. If the same herbicides are used every year in monoculture of paddy rice, the selection pressure for resistant weeds is therefore very high. The introduction of IMI-tolerant varieties of rice in Italy may have contributed to the selection of ALS-resistant weeds due to the increased use of ALS-inhibitors it triggered (Scarabel, Cenghialta, Manuello, & Sattin, 2012).

The most frequent and most concerning resistant grass weeds for European agriculture are *Alopecurus myosuriodes* (Alomy), *Lolium* spp., and *Echinocloa* spp. The presence of Alomy has been reported in 9 million hectares in the EU, and the plant is believed to have developed herbicide resistance in half of them (Petersen & Rosenhauer, 2014). *Lolium* spp. are among the major weeds in many European countries (Germany, Denmark, Spain, and Italy among others). In a survey conducted in the United Kingdom (UK), 70% of the population of *Lolium* spp. was proven to be resistant to at least one herbicide (Hull, Tatnell, Cook, Beffa, & Moss, 2014). Finally, resistant populations of *Echinocloa* spp. are an important issue in maize and rice fields in Italy, and are now expanding in France, Spain, and Portugal. Regarding broadleaf weeds, *Coniza* spp. is certainly the major concern, affecting orchard production. The species have evolved resistance to ALS-inhibitors but this issue can be controlled by different method, chemical or not. However, the resistance to glyphosate has been growing and is now widespread in perennial crops and along roadsides, becoming a threat for the agro-ecosystems (Rubin, Kleinman, & Matzrafi, 2014).

Many populations of resistant weeds have therefore appeared in the EU, and more will come. Up to now, most can be controlled by using different herbicides or a non-chemical weed control strategy, such as crop rotation or mechanical techniques. However, those that are left can pose serious agronomic and economic challenges to agricultural systems if the issue is not properly addressed. This can be the case with the species cited above that have developed multiple resistance (one single weed population resistant to numerous herbicides, of the same MoA or not). For those, proper weed management systems have to be adopted.

Economics of Herbicide Resistance in the European Union

One of the questions addressed by the economics of weed resistance is whether farmers should invest in preventive action to delay or avoid the onset of resistance, or rather manage the resistant weed populations when they appear in their fields. The literature (Pannell & Zilberman, 2001; Weersink et al., 2005) has shown that it is optimal to adopt strategies to delay herbicide resistance only in certain conditions: (i) the additional cost of a preventive strategy is not too expensive compared to the cost of the "non-preventive" strategy, (ii) the cost of resistance (i.e., the differential between the cost of the preventive strategy and the cost of the management of the resistance) is high, and (iii) the probability of the onset of resistance is high if no preventive actions are taken. For adoption of resistance-delaying strategies, it is essential that farmers believe that resistance can be delayed and that their management is crucial to achieve it, and that in the long run this will be beneficial to them. In some cases, at least, these conditions are met (e.g., Llewellyn et al., 2002, 2007).

There have been fewer economic studies on the issue in the context of European agriculture than in other settings, such as in North America or in Australia. However, one study has analyzed the cost related to the resistance of Alomy for growers of winter wheat in England (Orson, 1999). It has shown that the cost of resistance is about 180 GBP per hectare, while the cost of a particular strategy for delaying resistance in a particular farming context was estimated to be around 91 GBP per hectare. In addition, the lower the output price of wheat, the higher was the impact of the onset of resistance on the farm profits. The same study also investigated the cost of sulfonylurea resistance in paddy rice production in Italy. Again, the results showed that the cost of the preventive weed control strategy was lower than the cost of resistance, although the likely effectiveness of the preventative strategy was not discussed.

The efficiency of alternative weed control methods (i.e. non-chemical) to control the population of Alomy in cereal crop fields has been reviewed recently by Lutman, Moss, Cook, and Welham (2013) for the UK. The authors have found that these cultural practices can have rather unpredictable results. For instance, soil cultivation operations such as plowing reduces the density of Alomy by 69% on average, but in some experiments it did increase this population by up to 82%. Other techniques such as delayed sowing dates, high seed density, or the use of competitive cultivars do not have inconsistent effects but still have variable results and are, on average, less effective in ensuring a reduction of weed density than herbicides. In sum, farmers may not be very likely to adopt alternative weed control strategies if they cannot rely on their efficiency.

Regarding farmer awareness of herbicide resistance issues, a recent survey of Danish farmers has shown that a large majority of farmers state that they know about the problem of herbicide resistance and that they take it into account when they make their decision about which herbicide to use on their fields. However, the same farmers also struggled to properly differentiate herbicides with different MoAs, a key aspect to select herbicides if resistance issues are considered (Jensen, 2014). In this respect, the Australian experience with herbicide group of MoA labeling could be useful for the EU (see above). Access to extension services and the independence, and possible liability, of farm advisers are other important subjects that are closely linked to farmer awareness of herbicide resistance.

A recent study simulated economic and environmental impacts of the adoption of GMHT maize in the EU (Tillie, Dillen, & Rodríguez-Cerezo, 2014), considering the risk of herbicide resistance development. This work has shown that a large majority of EU farmers would adopt this technology (from 60% to 98% of farmers, depending on the country) if no anti-resistance strategy was required. In presence of herbicide resistance, the potential adoption would significantly decrease, but the technology would still be attractive for a large proportion of farmers (between 14% and 86%). Regarding the environmental aspects, the results showed that the shift from a broad-spectrum herbicide to a diversified herbicide program to delay or manage the development of resistant weeds erodes significantly the initial environmental benefits of adopting GMHT maize. The introduction of GMHT technology in the EU—as for any other innovation such as a new herbicide—should therefore be accompanied by adequate stewardship guidelines in order to preserve its benefits in the longer run.

The Future: Prospects, Challenges, and Research Questions

Farmers in the EU are facing a situation that is characterized by a reduction of the available chemical solutions for the control of weeds in their fields. In addition, the pipeline of new active ingredients looks rather dry, and the long-awaited miracle solution, a new herbicide MoA, could still be a long time coming. This situation, combined with an inappropriate use of the remaining herbicides, is paving the way to the continuous development of weed resistance.

In fact, the European legislation regarding the use of pesticide in agriculture is likely to become more stringent in the future, while national Member States can also enforce additional usage restrictions. At the EU level, the phasing out of endocrine disruptors in agriculture, which include many herbicides, will also occur in the coming years (Jones, Garthwaite, Wynn, & Twining, 2013). Some important herbicides may be affected. In addition, various Member States have also endorsed national action plans (NAP) for pesticide-use reduction, which varies by objective (quantitative targets or not) and levels of obligation for farmers. For instance, Denmark has set quantitative targets for the treatment frequency index in sensitive areas and mandatory buffer zones around water courses, while France has established an objective of a 50% reduction of pesticide use, where possible, in the framework of the "Ecophyto" plan. Germany and the UK, among others, have also implemented a NAP.

While the purpose of such restrictions is evident and motivated by scientific assessment of the negative impacts of pesticides on the environment and/or human health, the negative consequences on agricultural systems and farm operations also need a proper assessment. If farmers are not well advised, they may adopt counterproductive weed control strategies—such as the reduction of herbicide rates of application—to doses that are below the efficiency level and that will favor the selection of resistant weeds. Too often, when farmers are faced by issues of resistant weeds, they are told to improve the efficiency of the weed control, without adapting their agricultural system or adopting nonchemical weed control practices. Their response to the problem is usually based on herbicide mixtures. In fact, this results in the building up of the existing resistance together with the selection of new resistances within the same weed population. Currently, the control of weed in cereals fields in the EU relies largely on ALS inhibitors because of their large spectrum of action against grass weeds. However, they are more prone to resistance development than other classes of herbicides. It is likely that the repeated use of ALS inhibitors will lead sooner or later to their dramatic loss of efficiency, depriving European farmers of their favorite weed control option in cereal production.

In sum, the challenge is to break with the current practices for weed control still used by too many farmers in the EU, which are generally just a series of ad hoc short-term decisions aimed at resolving the last problem of herbicide resistance at the lowest cost, with no anticipation of the possible risk of the general strategy. Instead, it is necessary to return to coherent agronomic practices. In parallel to the implementation of the EU legislation or NAP for herbicide use, farmers should be encouraged towards the use of alternative weed control strategies, such as integrated weed management or crop rotations. Researchers can also contribute to this objective by helping in the design of innovative weed control strategies to avoid the development of herbicide resistance. Identifying the most efficient incentives for the adoption of preventive weed control strategies is a necessary goal.

A US Perspective

Herbicide resistance is not new to the United States (for example, episodes of resistance to 2-4D in the 1950s and triazine herbicides in the 1970s). The rapid adoption of HT canola, corn, cotton, soybean, and sugar beet in North America since the mid-1990s was accompanied by a dramatic reduction in the diversity of weed control tactics and intensified ecological selection pressure that ushered in a new era of HR weeds (Frisvold & Reeves, 2014). Importantly, the possibility of a "silver bullet" technological solution from the discovery of a new MoA, as has happened with past HR episodes, appears nil according to industry sources (Duke, 2012).

A National Research Council (NRC) committee concluded weed resistance to glyphosate was an escalating problem, noting that two weed species were already resistant to glyphosate (NRC, 2010). That conclusion was prescient—14 species in the United States and 32 species worldwide are now resistant to glyphosate (Heap, 2015). Further, the number of weeds resistant to two or more sites of action has been rising at a similar rate (Heap, 2015).

Economic and Environmental Implications of HR Weeds

Costs of glyphosate-resistant (GR) weeds can be significant. In a study surveying weed specialists nationally, Carpenter and Gianessi (2010) reported average additional costs to control GR Palmer amaranth of $40/hectare for corn, $52/hectare for soybeans, and $74/hectare for cotton. Costs of resistant weeds can be especially large in the first year they infest a field because by the time that growers realize glyphosate applications have been ineffective, weeds have grown too large to be controlled by other post-emergence herbicides (Weirich et al., 2011). Growers may have to resort to hand weeding;

these costs can reach $100 per hectare or more, with some estimates as high as $371 per hectare (Riar, Norsworthy, Steckel, Stephenson, & Bond, 2013; Shurley, Smith, Culpepper, & Roberts, 2010). In severe cases, growers may abandon fields altogether (Culpepper, Whitaker, MacRae, & York, 2008). A 2012-13 survey of cotton producers in 13 southern states revealed that "the proportion of farmers in the sample who indicated they had total weed control costs of $50 or more per acre nearly doubled with the emergence of herbicide-resistant weeds on their farm" (Zhou et al., 2015).

The NRC (2010) committee warned that if actions were not taken to promote improved herbicide stewardship, several environmental risks would materialize. The negative effects could stem from farmers resorting to alternative herbicides with higher toxicity quotients that could diminish water quality and wildlife resources. Compared to many competing herbicides, glyphosate has certain desirable environmental characteristics (Nelson & Bullock, 2003). It degrades relatively quickly in the environment. Unlike water-soluble herbicides such as atrazine, it is less likely to reach groundwater sources. Further, it has lower toxicity ratings, given by the US Environmental Protection Agency (EPA), than many other herbicides. Nelson and Bullock (2003) estimated that widespread adoption of GR soybeans would lead to significant reduction in the overall acute mammalian toxicity of herbicides used. Gardner and Nelson (2008) later estimated that a switch away from GR crops because of GR weeds would lead to increases in the acute mammalian toxicity of herbicides used on soybeans and cotton. There are also concerns that HR weeds could discourage continuation of conservation tillage in many areas (Culpepper et al., 2012; Price et al., 2011; Steckel & Culpepper, 2006). The soil disturbance from tillage generally causes higher erosion with sediment, nutrient and pesticide-laden runoff, and more carbon dioxide emissions from oxidizing soil particles.

The private and environmental costs of HR weeds implies large potential gains from preventing (or at least delaying) resistance. A bio-economic modeling analysis of glyphosate resistance in corn and soybean production concluded

> "Choices that manage resistance (1) use glyphosate during fewer years; (2) often combine glyphosate with one or more alternative herbicides; and (3) most importantly, avoid applying glyphosate in consecutive growing seasons. As a result, glyphosate resistance is managed more cost effectively, and after about 2 consecutive years of managing resistance, the cumulative impact of the returns received exceeds that received when ignoring resistance" (Livingston et al., 2015, p.7).

Developing New Strategies

Resistance management (RM) strategies have been advanced by weed scientists, extension educators, and industry teams (e.g., Herbicide Resistance Action Committee, 2015; Norsworthy et al., 2012). Despite these efforts, expert assessments suggest that the resistance problem is not abating but likely intensifying (Weed Science Society of America [WSSA], 2014). Most of the efforts to promote the adoption of integrated weed management have employed voluntary education and technical assistance approaches. While voluntary conservation programs can induce adoption by some farmers, their record has been uneven and found lacking in efficacy and efficiency unless targeted carefully and accompanied by adequate subsidies (Ervin, 2013). Aware of these limitations, the chemical-seed industry has offered incentives to farmers to diversify their herbicide applications (Volkmann, 2010). The effects of these industry-led programs must await further evaluation, but early estimates suggest that significantly higher funding will be necessary to cover a majority of the infested crop acres (Mitchell, 2011).

Herbicide resistance has many characteristics of a "wicked problem" that have uncertain natural and human system interactions that vary across locations, have no uniform cause-effect relationships, and have no standard template for developing solution approaches (Jussaume & Ervin, 2015). To tackle such a complex problem set, the NRC committee recommended that

> "[f]ederal and state government agencies, private sector technology developers, universities, farmer organizations, and other relevant stakeholders should collaborate to document emerging weed-resistance problems and to develop cost effective resistance-management programs and practices that preserve effective weed control in herbicide-resistant crops" (NRC, 2010, p. 14).

In doing so, they endorsed a public-private sector interdisciplinary approach to the problem. The committee further noted that

> "[f]armers of HR crops should incorporate more diverse management practices, such as herbicide

> rotation, herbicide application sequences, and tank-mixes of more than one herbicide; herbicides with different MoAs, methods of application, and persistence; cultural and mechanical control practices; and equipment-cleaning and harvesting practices that minimize the dispersal of HR weeds" (NRC, 2010, p. 14).

A public-private task force was formed in 2011 to implement the NRC committee's recommendation. The members included weed scientists, economists, sociologists, government agency staff, crop advisers, and industry representatives who are actively engaged on HR topics. The task force co-sponsored a national summit on HR issues in 2012 with the National Research Council to assemble intelligence on the extent of HR problems and begin exploring potential approaches (NRC, 2012). This activity raised the public profile of the HR problem in the United States and led to a second national summit in 2014 on developing innovative approaches (WSSA, 2014). In the process of offering the summits, the task force sought to promulgate the notion that HR, although governed by biophysical processes such as weed pollen and seed dispersal, was as much a human problem as one driven by natural systems and technology. Hence, strategies for the eventual control of HR need to integrate theories and data from the social sciences with those from the natural sciences to a degree that had not been previously done (Ervin & Jussaume, 2014).

Because of increasing national attention, two federal agencies took actions to address the HR problem. First, the Secretary of Agriculture announced a set of actions to devote more program resources to implementing effective HR and weed management approaches (US Department of Agriculture [USDA], 2014). These programs combined the efforts of the Animal Plant and Health Inspection Service (APHIS), which regulates the releases of genetically engineered crops, and the Natural Resources Conservation Service (NRCS), which provides financial assistance under its Environmental Quality Incentives Programs for integrated weed control practices. A second activity by the US EPA was also directly linked to the rising prominence of HR issues. In 2014, EPA announced new label language and reregistration requirements in the deregulation of the Enlist Duo stacked herbicide for commercial sale. This new set of requirements marked an important step in the EPA considering the effects of HR on the quality of the nation's environment.

In addition to policy actions, new US research projects are seeking to better understand the extent of the HR problem and the motivations and barriers that influence integrative weed management. One project funded by the USDA Agricultural Food Research Initiative (AFRI) in 2014 is "Integrating Human Behavior and Agronomic Practices to Improve Food Security by Reducing the Risk and Consequences of Herbicide-Resistant Weeds" (Owen, Martin, & Meyer, 2014b). In this nearly $1 million effort, weed scientists, economists, and sociologists from seven universities along with the USDA Economic Research Service will conduct the first primary survey of growers in five major crop-production regions about HR issues. Numerous regional and state research efforts on HR are also underway or have been proposed.

The entry of EPA into HR management raises the issue of regulating herbicide use. Unlike most industries, voluntary programs with technical assistance and subsidies have been the norm for agricultural conservation and environmental issues, with the exception of pesticide registration and confined animal waste management. The voluntary approach stems from the technical infeasibility and economic cost of regulating diverse nonpoint agricultural environmental problems and the political power of the industry to ward off regulatory efforts (Ervin, 2013). There are several reasons to believe that bottom-up control of environmental problems in agriculture may be more cost-effective and sustainable than top-down prescriptive regulations (Ervin & Frisvold, 2015). First, the heterogeneity of the industry and the specific local resource conditions suggest that uniform practices may be inappropriate and cause excessive costs for many growers. Such approaches lack the flexibility to exploit local resource knowledge and experience with production technologies. Second, the administrative and transaction costs of implementing a top-down regulatory system would very likely be large for such a diverse industry.

Mobility of Resistance Causes Special Challenges

Herbicide resistance also poses social challenges. Miranowski and Carlson (1986) highlighted the critical role of pest mobility in designing appropriate policies to manage resistance. Early research on managing pest resistance concluded that mobility was a problem with insect pests, but not weeds (Clark & Carlson, 1990; Gould, 1995; Pannell & Zilberman, 2001). However, recent research suggests mobility problems may be greater than earlier believed (Hanson, Shrestha, & Shaner, 2009; Llewellyn & Allen, 2006; Llewellyn & Pannell, 2009; Lu, Baker, & Preston, 2007; Marsh et al., 2006; Michael, Owen, & Powles, 2010; Wilson, Tucker, Hooker, LeJeune, & Doohan, 2008). If HR mobility is significant, community-wide action may be required to effectively manage its spread.

With mobility, the susceptibility of weeds to a specific herbicide is a resource shared in common by all operators in the community. Under such conditions, the collective long-term interest of farmers is to conserve the herbicide's usefulness. Yet, farmers have an individual short-run incentive to use the herbicide without considering effects on resistance because they are unsure their neighbors will reciprocate with sound stewardship. It is an empirical question whether mobility of resistant weeds presents a common-pool resource (CPR) problem. Experiences from Australia, where there has been rapid depletion of herbicide efficacy on relatively large operations (where neighbors would have less influence) suggest that the problem is more of a private, intertemporal one. There is evidence, however, from the United States that growers *believe* their neighbors affect their own weed resistance (Wilson et al., 2008). Work by Livingston et al. (2015) suggests that common-pool problems may be important in some cropping systems, but not others.

The operative question then becomes, what type of social organization can effectively manage this CPR? Early writings on the tragedy of the commons focused on the need for public regulation, i.e., Hardin (1968). Subsequent investigations documented the success of private, community-based initiatives under certain natural resource and social conditions (Ostrom, 1990). Three stereotypical approaches can be envisioned. The first is to impose government regulation requiring all growers to comply with prescribed practices that are enforced with noncompliance penalties. Historically, such command-and-control approaches to resource management have proven costly. This can occur because uniform standards do not provide adequate flexibility or incentives for innovation, while monitoring and enforcement can be expensive (Field & Field, 2012).

A second approach offers payments or rebates (public or private) to resource users to alter their behavior. Payment schemes are more popular with those being regulated, but can suffer from inefficiencies similar to regulations. One limitation of such payments, whether publicly or privately financed, is that practice adoption may not actually change behavior, termed additionality (Claassen, Horowitz, Duquette, & Ueda, 2014; Segerson, 2013). If producers receive payments for practices that they have already adopted or would adopt because they are profitable, the payments do not lead to additional resource conservation. In this case, the payments simply become income transfers to farmers. Another limitation is that the payments may only be eligible for prescribed practices that do not account for variations in resource conditions across farms. Finally, a basic difference over regulations is that the cost of the inefficiencies are borne by taxpayers (or private funders) rather than those regulated.

The third, community-based (CB), approach relies on programs led by growers themselves. Here, growers are actively involved in the design, financing, and implementation of programs. Usually, there is collaboration with industry, government, and universities. But the role of government is distinctly different in CB approaches from that of the top-down regulation or incentives. It is often as a facilitator and provider of scientific knowledge and complementary investments, such as administering a resource monitoring system. Implementation and compliance under CB schemes still require significant design and monitoring effort and cost as well as a clear delineation of relevant stakeholders. While growers may benefit from government technical and financial assistance, they often must also provide additional funds through internal support schemes.

Design Principles for Community-based Approaches

Ostrom (1990) synthesized eight design principles for stable local CPR institutions that can improve their chance of success.

1. *Establish clearly defined boundaries.* Two types of boundaries must be identified—the geographic area that must be governed, and the parties who must be engaged in the CPR effort. The geographic boundaries depend upon the zone of weed pollen and seed mobility, while the boundary of parties may include others who exercise control over weeds in farming areas, such as local governments or utilities on public rights of way.

2. *Develop congruence between the appropriation and provision rules for the common resources that are adapted to local conditions.* This principle capitalizes on the local knowledge of farm operators and assures congruence between the costs incurred by resource users, farmers in this case, and the benefits

they receive from participation in the CB action. This involves meeting both benefit-cost and fairness tests for the rules.

3. *Implement collective-choice arrangements that allow most resource appropriators to participate in the decision-making process*. This empowers resource users to participate in the CPR decision process and take advantage of the local knowledge of the special resource and social conditions, leading to better system administration.

4. *Conduct monitoring by monitors who are part of or accountable to the resource appropriators*. This requires that monitors are appointed by the CB program and are accountable to the full set of resource users. Monitors should benefit by improved resource condition or otherwise rewarded if they perform satisfactorily (i.e., monitoring is incentive compatible). The monitoring system identifies resource users not in compliance and collects information on the CPR resource conditions over time.

5. *Institute a scale of graduated sanctions for resource appropriators who violate community rules*. Experience with CPR programs shows that some portion of resource users will not comply (Ostrom, Chang, Pennington, & Tarko, 2012). If the sanctions are visible and significant, a higher level of compliance should ensue. Graduated penalties send a signal to resource appropriators that larger departures impose proportionately higher costs on other resource users. The body responsible for administering the sanctions can be within the CB organization or a public agency.

6. *Create mechanisms of conflict resolution that are cheap and easily accessible*. Conflicts between CPR users are inevitable. Access to cheap and easy conflict resolution enhances the probability of decentralized solutions to CPR management problems. Some CPR institutions rely on court systems (e.g., water sharing arrangements), while others have privately administered bodies that adjudicate appeals or charges for non-compliance.

7. *Higher-level authorities recognize self-determination of the community*. Effective CB programs must have legal standing to be free from challenge by external parties. This surety fosters long-term planning and investment and vests the local parties.

8. *For larger common-pool resources, organization in the form of multiple layers of nested (polycentric) enterprises may be required*. If CPR issues span multiple jurisdictional boundaries, other entities at distant points or at higher levels of administration may be required to assure sufficient coordination and effective action to conserve the common pool resource.

These principles may not apply to particular CPR cases. Agrawal (2003) has critiqued this synthesis work, noting exceptions and questioning how firmly causal relationships have been established. In contrast, however, in a study of 91 CPR management programs, Cox, Arnold, and Tomas (2012) found that each of the above design principles was well supported empirically.

Lessons from Past Community-based Programs

Ervin and Frisvold (2015) evaluated several different agricultural CB programs to consider what useful lessons they may provide for CB RM programs. They considered area-wide insect control programs, insect eradication programs, area-wide invasive weed control programs, weed control districts, Cooperative Weed Management Areas, and Weed Prevention Areas. These programs shared several critical features. First, local, private land managers were actively involved in defining the design and geographical scope of these programs, in addition to monitoring and implementing the program. Second, local entities did not just participate in these programs, but had key leadership roles in program implementation and evaluation. Third, successful implementation of these programs relied on local social networks. Fourth, while these programs had (to varying degrees) mandatory requirements and regulatory authority, local farmers, ranchers, or political jurisdictions agreed upon these mandates and regulations beforehand.

Several lessons emerged from studying these programs. First, successful programs have a solid theoretical understanding of biological mechanisms as well as an understanding of how strategies might succeed (or fail) in different agronomic settings. A strong scientific underpinning is needed to receive financial and technical assistance from federal agencies and acceptance by growers. Scientific principles must also be communicated effectively. This requires strong linkages between university research and extension programs. Second, social scientists are actively involved from the outset of programs. Understanding socio-economic dimensions are important for understanding the social context of current practices, barriers to adopting new practices, and group dynamics. Economic analysis can estimate potential gains of program implementation *ex ante* and economic benefits of successful programs *ex post*.

Studies emphasize the importance of having a strong local leader or coordinator to maintain program focus. In some cases, full-time coordinators were hired. This acknowledges the fact that CB efforts entail significant transactions costs that can be an overwhelming time commitment for most farmers. Coordinating CB activities may need to be a full-time responsibility.

Detailed monitoring, data collection, reporting, and evaluation need to be ongoing. This is important for establishing baselines and monitoring program progress. In some cases, grower groups may already be in place with monitoring and practice requirements. Pest eradication areas are examples. Groups and institutions active in these prior programs may serve as a basis for self-organization around herbicide RM. Certain RM practices are readily observable to outside evaluators and neighboring growers (for example, use of crop rotations and cover crops). Readily observable land-use practices have the additional advantage of providing neighboring farms visible evidence of compliance.

Several programs stressed the need to clearly establish geographic boundaries. This is critical to prevent in-migration of resistant weeds from outside a RM area. Adopting comprehensive boundaries presents certain challenges, however. First, as geographic scope increases, agricultural cropping systems and producer types (hobby farms vs. commercial operations) diversify. Different groups may have different incentives and capacities to manage resistance. Attaining group cooperation may require additional transaction costs and transfer and support mechanisms to encourage adoption. Further, purely commodity-based organizational structures may be insufficiently comprehensive. Within agriculture, cross-commodity approaches may be necessary. Groups outside agriculture may also need to participate. Weed management along roads, rights of way, and ditch banks requires actions off farmlands and by non-agricultural land managers. Agencies with authority over public lands, such as conservation areas, can affect herbicide resistance by their management of weeds and waterways. The participation of public land managers (especially in the West where so much of the land is publicly managed) will be necessary for comprehensive RM.

Results also suggest challenges that CB RM programs may face. Some programs emphasized the importance of simplicity of practices in encouraging adoption. This may be a particular challenge for CB herbicide resistance programs. Recent trends have been toward (over) simplification of weed management systems and reduced diversity of tactics. Diversified RM programs will likely be more complex and management intensive. Managing *to avoid* resistance requires proactive management. Yet, studies have found that demand for participation in CB programs is relatively low among farmers not currently facing a problem. Resources developed to assist in the establishment of Weed Prevention Areas (e.g., Christensen, Ransom, Sheley, Smith, & Whitesides, 2011; Ransome & Whiteside, 2012) may assist in developing herbicide-resistance prevention programs.

Conclusions

The experience of HR weeds across the three regions illustrates the need for diverse weed control tactics that include non-chemical control measures as well as chemical control. While growers have relied on a succession of new compounds with new modes of action (MoAs), no such new MoAs have been commercially developed in decades. There are no "silver bullets" on the horizon. Individual MoAs are exhaustible resources, and there has been growing recognition of the constraints that implies.

This all raises the question of what is meant by "resistance management." Does it mean adapting to HR weeds once they emerge? Does it mean managing weeds to delay resistance (i.e., prevention)? Is it both? Australia's experience illustrates that profitable farming can continue, even with pervasive resistance problems. It also illustrates that diverse weed control strategies (including non-chemical control) will be crucial for this continuation. Along with renewed appreciation of the importance of diversity in tactics, there is appreciation of the importance of aggressive control of weed seed banks as a critical RM strategy.

Weeds will evolve in response to efforts to control them and this will at least partially thwart those efforts. So, technologies and institutions must also evolve in response. This means that addressing HR weeds will require ongoing public and private R&D. Regulation and approval of chemicals and GM seed varieties and herbicide resistance are inter-related, so policy should ideally consider these various issues simultaneously. The more individual chemicals are applied, the faster weeds will evolve resistance to them.

One thing has become clear, however. Decisions about approval or cancellations of pesticides and approval of new GM crops will be required to take account of implications for RM. There will be environmental as well as economic trade-offs associated with different regulatory decisions. These decisions will affect substitution between chemicals with different environmental damage profiles and also affect use of tillage, which also has environmental implications (e.g., sedimentation, erosion, and fossil fuel use).

Economics can play a central role in informing debates concerning HR weed management. First, there is the traditional economics contribution of evaluating the profitability of different resistance-management strategies. This can identify barriers to adoption and suggest policies to overcome those barriers. Economists can also estimate the costs and benefits of public policies to address HR weeds. This includes costs and benefits of regulatory approval mechanisms for GM crops, of pesticide regulation, and of programs to encourage voluntary adoption of resistance management (RM). Economists can identify where common-property resource problems (i.e., resistant weed mobility) impose barriers to RM, information which can assist in designing and evaluating community-based RM programs. Equally important, economists can identify conditions where RM is a dominant strategy regardless of neighbor behavior.

Finally, institutions, farm structure, the extent of GM crop deployment, and environmental regulations regulatory systems are quite different across continents. Solutions to HR weeds will have certain commonalities. Yet, there may be few “one-size-fits-all” solutions. It will be important to craft policy responses to specific agronomic, environmental, and institutional settings.

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Authors' Notes

The opinions expressed are those of the authors only and should not be considered as representative of the European Commission's official position.