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Abstract. Weed control in the U.S. Midwest has become increasingly herbicide-centric due to the adoption of herbicide-tolerant (HT) crops in the 1990s. That integrated weed management (IWM) practices, including ecological and mechanical controls, are scarcely used is concerning. IWM would be a more sustainable form of farming for two reasons. First, it would reduce the negative health and environmental externalities associated with herbicide use. Second, it would reduce the selection pressure on weed populations and the development of weed resistance to some herbicides, thereby reducing the uncertainty of the long-term effectiveness of herbicidal weed control. In this context, we develop an economic framework to clarify the interplay among the different market failures that either contribute to the herbicidal "lock-in" or make it problematic. We then analyse the evidence for and perceptions of these market failures based on twenty-four semi-structured interviews with farmers and experts conducted in 2017, as well as on discussions in the academic literature. To this end, we put into perspective the possible self-reinforcing effects in the adoption path of HT crops, such as increasing farm size, changes in farm equipment, increasing incentives for simplified crop rotations, and the loss of practical knowledge of IWM practices.

Keywords: herbicide-tolerant crops; integrated weed management; health and environmental externalities; weed resistance; lock-in

1. Introduction

Weeds in farm fields can deprive crops of water, nutrients, and light, and so lower crop yields. In the U.S. Midwest, the region of the world studied in this article, chemical herbicide application rapidly became the central method of weed control after it was developed in the 1930s. Up through the 1990s, weed control relied on selective herbicides, each working on particular groups of weeds. These herbicides were used in combination with mechanical methods for weed control, consisting of tillage and cultivation. In the late 1990s, the advent of herbicide-tolerant (HT) crops, mainly with tolerance to glyphosate, further simplified weed control. Glyphosate is a nonselective herbicide, controlling many different types of plant species by inhibiting an enzyme necessary for plant growth. Glyphosate-tolerant (GT) crops, developed through genetic modification, carry the gene coding for a glyphosate-insensitive form of this enzyme, obtained from a soil bacterium, and conferring crop tolerance to glyphosate once incorporated into the plant genome. They allowed farmers to spray fields with glyphosate after crop emergence, and so kill weeds without killing the crop, notably reducing the need for mechanical weed control. In 2017, GT crops covered 94% and 89% of U.S. soybean and corn areas, respectively, almost entirely replacing previous conventional crop varieties treated with selective herbicides.

Two sustainability issues confront herbicide-centric methods of weed control. First, the scientific literature shows that pesticides, among them herbicides, often have harmful health and environmental effects (Pimentel, 2009). Second, the repeated use of herbicide-centric methods often leads to weed resistance to the herbicides used (Duke, 1996), reducing their effectiveness over time, and indeed weed resistance to glyphosate is rapidly increasing (Heap and Duke, 2018). Thus far, farmers have mainly controlled resistant weeds by applying selective herbicides in addition to glyphosate on GT crops (Bonny, 2016). Agrochemical companies have also recently developed HT crop varieties that are tolerant to selective herbicides in addition to glyphosate; crops tolerant to dicamba herbicide were commercialized in 2017 and crops tolerant to 2,4-D were commercialized in 2018. However, while increasing resistance to the selective herbicides used to supplement glyphosate seems inevitable, no new herbicide modes of action have been discovered for more than thirty years (Heap and Duke, 2018). It is not certain that herbicide manufacturers will be able to develop new synthetic products with new modes of action that can effectively control weeds and pass the increasingly demanding regulatory requirements aimed at controlling their effects on human health and the environment (Duke, 2012).

Integrated weed management (IWM) is an alternative to herbicide-centric weed control, and it at least partially addresses both sustainability issues. IWM integrates multiple weed management methods, including not only chemical and mechanical weed control, but also ecological methods such as crop rotation, cover-cropping, intercropping, planting of competitive cultivars, and the biological control of weeds with insects and pathogens. However, wide-scale IWM implementation would require major changes from current cultivation practices and likely worsen farmers' complexity and costs of weed management. Indeed, ecological weed control has diminished over time; currently, it is used only marginally. The great majority of Midwestern farmers today rotate corn and soybeans; longer rotations involving wheat, oats and alfalfa are extremely rare.

In this context, our aim is to describe the factors that may hinder widespread movement away from the use of HT technology for weed management towards a more sustainable form of agriculture relying on IWM. More precisely, we seek to analyse the extent to which the increased reliance on HT technologies may have generated self-reinforcing effects, making the adoption of IWM practices more difficult and costly than would have been the case had herbicide-resistant crops never been developed. Mortensen, Egan, Maxwell, Ryan, & Smith (2012) proposed that the development of crops tolerant to multiple herbicides leads to a decline in the science and practice of IWM and that the increased consolidation of the seed and chemical industries is making it more difficult for growers to find high-yielding varieties that do not also contain transgenic herbicide resistance traits. They also argue that the marketing of cultivars tolerant to 2,4-D and dicamba may compel nearly all growers in a region to adopt them once some critical mass of growers in the region adopts them. In fact, soybeans and corn are extremely sensitive to 2,4-D and dicamba, and non-tolerant soybeans and corn could be injured by the application drift of 2,4-D and dicamba from other fields. This "lock-in" of HT technology has not been considered in the more general literature attempting to gauge the welfare impacts of HT technology adoption.

The concept of lock-in has been used in several discussions related to agriculture (Cowan and Gunby, 1996; Magrini et al., 2016; Vanloqueren and Baret, 2008; Wilson and Tisdell, 2001). We complement this literature by presenting a framework for the discussion of the market and policy failures associated with weed control, including the common-pool nature of weed susceptibility to herbicides and the environmental and health externalities of herbicides. We also introduce a framework for examining lock-in, different from those presented in previous articles. We base our framework on the concepts of *switching costs*, *network effects*, *path dependence in innovation possibilities*, and *policy persistence*. We then use this framework in a discussion of the evidence for and perceptions of the market and policy failures that accompany the use of HT technologies and the barriers to IWM. We base the discussion on evidence from academic articles, public information, and 24 interviews conducted with university experts, regulators, and farmers in 2017.

2. Weed-Control Market and Policy Failures

2.1. Previous Analyses of HT Crop Adoption Neglect Certain Types of Failure

An abundance of the economic literature examines the effects of adopting HT crops in terms of changes in production and management costs, farm profits, the profits of upstream seed and herbicide suppliers, and consumer surplus. For the U.S., empirical studies have mainly focused on HT soybeans, and used market equilibrium models to analyse the welfare effects of adoption (e.g., Price, Lin, Falck-Zepeda, & Fernandez-Cornejo, 2003). This literature concludes that the production cost savings from HT crops lead to aggregate welfare gains.

Though not always accounted for in empirical studies, two HT-market failures have been studied thoroughly in the theoretical agricultural economics literature. First, the monopoly rights granted for GT seeds have allowed the innovator to extract monopoly rents (Moschini and Lapan, 1997). Second, some perceive foods derived from GMOs to be of inferior quality, and the costs of segregation and identity preservation of non-GMOs create a market failure (Desquilbet and Bullock, 2009).

Other possible types of market failure associated with HT crop adoption have received less attention in the economic literature. First, most of the said literature predated significant weed resistance and considered only the short-term cost savings. Second, the negative health and environmental externalities of herbicides were ignored. Third, possible dynamic inefficiencies caused by self-reinforcing effects in an ex-post inefficient direction were under-considered. These market failures are discussed below.

2.2. Weed Susceptibility to Herbicides Is a Common-Pool Resource

Hueth and Regev (1974) initiated the economic literature on pest and weed resistance management. In economic terms, herbicide use involves joint management of two natural resources: the weed population, a detrimental renewable resource, and the stock of susceptibility (non-resistance) of the weed population to herbicides, a beneficial resource. Optimal herbicide application presents an intertemporal trade-off between controlling the present weed population and preserving future herbicide susceptibility. Because weed seeds and pollens escape their fields of origin, farmers enjoy the immediate benefit of herbicidal weed control but share weed susceptibility and future weed populations as common-pool resources. In economic terms, the lack of property responsibility for weed populations and property rights to weed susceptibility creates a market failure: the market cannot optimally allocate, spatially or temporally, the two resources (Ambec and Desquilbet, 2012). Coordination or regulation may be warranted to provide individual farmers with incentives to apply resistance management strategies best-suited for the farm community. However, no U.S. laws or regulations currently attempt to offset the market failures just described. We examine causes of the dearth of regulations in section 3.

2. 3. Herbicides Create Negative Health and Environmental Externalities

Herbicides are detrimental to human health and to the environment, although the extent of this externality is hard to quantify, varies by herbicide, and depends on the interactive effects of the different chemicals in the applied herbicide "cocktail" (Bourguet and Guillemaud, 2016). The adoption of IWM practices would reduce herbicide use and therefore these negative externalities (Davis, Hill, Chase, Johanns, & Liebman, 2012).

More evidence exists of the health effects of pesticides for agricultural workers than for the general population. Occupational exposures to pesticides are linked to a number of different cancers (Alavanja and Bonner, 2012). Herbicides may also be associated with health outcomes other than cancer for agricultural workers: for example, Shrestha et al. (2018) found evidence of an increased risk of hypothyroidism associated with the 2,4-D, dicamba and glyphosate herbicides. Herbicides also impact the aquatic life, affecting the biological processes and biodiversity in water (Davis, Hill, Chase, Johanns, & Liebman, 2012), and may be deleterious to soil microbial communities, soil biochemical reactions and soil enzymes (Hussain et al., 2009).

The academic literature on the economic impacts of HT crops usually considers glyphosate to be more environmentally benign than the herbicides it replaces, thereby reasoning that the adoption of HT crops has provided environmental benefits (e.g., Nelson and Bullock, 2003). However, the environmental and health impacts of glyphosate-based herbicides are currently subject to controversy, notably sparked after the International Agency for Research on Cancer (2017) classified glyphosate as a probable human carcinogen. The main points of controversy pertain to the greater effect of glyphosate and co-formulants in glyphosate-based herbicide formulations than of glyphosate alone and to the influence of the datasets and methods used to evaluate the toxicological effects (Benbrook, 2019). In addition, in a context where limitations in the number of agricultural workers included in cohort or control-case studies and in the measure of their exposures make it difficult to document the effect of particular pesticides, recent articles in epidemiology concluded that glyphosate was associated with an elevated risk of some types of lymphoma (Leon et al., 2019; Zhang, Rana, Shaffer, Taioli, & Sheppard, 2019).

2.4. A Dynamic Market Failure: Lock-in and Its Causes

Arthur (1989) defines "lock-in" as occurring when a technology gains, even if by chance, a market advantage over competing technologies, and ends up dominating the market, even though it might not be more efficient. In our context, when herbicides or HT technology were first commercialized, both consistently provided higher farm profits than could IWM. However, this accounting neglects the costs of the negative externalities of herbicide use. Additionally, the spread of weed resistance lowers the profitability of herbicidal weed control. Our focus below is on the self-reinforcing effects ("lock-in") of the herbicide and HT technologies, which may have contributed to the dominance of herbicidal weed control.

Below, we present a framework featuring four causes of lock-in: *switching costs*, *network effects*, *dependence of the innovation possibilities frontier*, and *policy persistence*.

2.4.1. Switching Costs and Network Effects

The industrial organization literature discusses *switching costs* and *network effects* as the principal causes of customer lock-in to early choices. As defined by Klemperer (1995), "*a switching cost results from a consumer's desire for compatibility between his current purchase and a previous investment*", independent of other customers' choices. In contrast, network effects are self-reinforcing effects coming from the influence of each customer's decisions on other customers: "*network effects arise where current users of a good gain when additional users adopt it*" (Farrell and Klemperer, 2007). There are two types of network effects. Direct network effects arise if adoption by different users is complementary. A typical example is when users of a communication network directly benefit from its adoption by others because they have more opportunities for interactions with peers. Indirect network effects arise through improved opportunities to trade with the other side of a market.

Switching costs are socially detrimental when the tie between consumer transactions obstructs efficient buyer-seller matching. Switching costs and network effects may also limit the entry of new suppliers, creating a social cost of incompatibility (Farrell and Klemperer, 2007). In addition, the negative externalities of herbicides imply a welfare loss if the switching costs and network effects hamper the adoption of IWM practices.

2.4.2. Path Dependence in Innovation Possibilities

Lock-in can also result from the path dependence of innovation possibilities, which arises if the existing stock of knowledge influences the type of knowledge developed. This happens when past technological advances make future advances more profitable, as current researchers "stand on the shoulders” of their predecessors (Acemoglu, Aghion, Bursztyn, & Hemous, 2012).

2.4.3. Policy Persistence

Policy persistence is the tendency of a policy to be maintained or renewed, even when its original rationale no longer justifies continuance. Coate and Morris (1999) explain this bias towards the *status quo* as being the result of the adjustment costs that economic agents undertake to benefit from a policy. This costly response incentivises agents to persuade policymakers to maintain or renew an existing policy, even when the agents are *ex-ante* indifferent to competing policies.

3. Evidence and Perceptions of the Market and Policy Failures

3.1. Methodology

We used the concepts developed above about market and policy failures associated with herbicidal weed control to design questions for one-hour, in-person, and semi-structured interviews. We conducted 24 interviews in 2017 with ten university experts (agricultural economists, weed and crop scientists, and extension specialists), five regulators from the EPA and USDA, the representative of a producer association, a crop consultant, and seven farmers.

An extension specialist of University of Illinois helped to set up interviews with farmers of heterogenous farm sizes and farm ownership structures, and with the crop consultant. We initially sampled a group of fifteen university experts and six regulators or former regulators with recorded publications on the topic of HT crops, herbicide resistance, agricultural technology and IWM, as well as two environmental advocacy groups. Other prospective participants were selected through snowball sampling by asking interviewees to suggest, either in interview requests or in person, additional participants. In total, we contacted 25 experts from universities, three environmental advocacy organizations and ten regulators. Seventeen experts were finally interviewed, thirteen did not return emails, and eight were not available or declined. Most of those who declined suggested alternative contacts in the same department or institution. Most of the interviews, lasting between 45 minutes and an hour and a half, were conducted in person, and three were conducted via telephone or teleconference. All interviews were recorded with the permission of the participants.

In this section, we analyse the evidence and perceptions of these market and policy failures in light of the interview responses, academic literature, and other available public information.

3.2. The Adoption Path of HT Crops

3.2.1. Rapid and Widespread Adoption of GT Crops

GT crops were commercialized during a period of increasing weed resistance to existing selective herbicides for Midwestern soybean and corn production—with increased resistance to ALS-inhibiting herbicides being a case in point (Shaner, 2014). This initial weed resistance fuelled GT crop adoption (Owen and Zelaya, 2005) but appears not to be the main driver of GT crop adoption, as illustrated by this answer given by a farmer when asked whether he experienced weed resistance to herbicides prior to the commercialization of GT technology:

> I don't think so, I really don't think so. I mean, it's just that those other chemicals didn't work as well. It was not resistance. It was just, "well, they may work, they may not," depending on how big the weed was, when you sprayed, whether it cooled off that night, did you get a rain within a certain amount of hours, or they weren't actively growing, they were partially drought-affected. And then Roundup™ came, and if you got part of that plant sprayed with Roundup, that baby was dead. It just worked.

Indeed, the academic literature cites several initial economic advantages that fuelled the rapid adoption of GT crops (Fernandez-Cornejo and McBride, 2002). First, GT crops lowered weed-control costs. In addition to glyphosate being cheaper than the cocktail of selective herbicides it replaced, the costs of operator time and fuel were lower, as fewer tractor passes were needed in the fields each year. Weed identification ("scouting") costs were also much lower because glyphosate controlled such a broad spectrum of weeds. Second, controlling weeds with glyphosate provided farmers with important time flexibility: glyphosate could kill larger weeds than selective herbicides, widening the time window for spraying, and thus lowering the risk of rain and mud keeping heavy machinery out of the fields while weeds grew too large to kill. Third, because glyphosate controlled such a wide range of weeds, GT technology greatly simplified weed management, saving valuable management time for other activities (Gardner, Nehring, & Neson, 2009). Fourth, GT technology made the mechanical control of weeds (with interrow cultivators) unnecessary. Fifth, the development of HT crops reduced the use of pre-plant tillage techniques, again saving operators time and money. Using 1988-2006 state-level panel data, Fernandez-Cornejo, Hallahan, Nehring, Wechsler, and Grube (2012) found that HT adoption reinforced the adoption of conservation tillage practices. Perry, Moschini, and Hennessy (2016) reported that GT soybeans and conservation tillage are complementary practices. Finally, using data from a nationwide, early-2000s survey of soybean farmers, Fernandez-Cornejo, Hendricks, and Mishra (2005) found, after controlling for other factors, that adoption of HT soybeans was positively and significantly correlated with off-farm household income.

Our interviewees discussed all aspects of the cost reductions mentioned above. One farmer summarized the general tenor of the conversations about incentives for GT technology adoption as follows:

> Economics. […] It worked, it flat worked.

Another farmer told us,

> It was a win-win situation that you didn't even have to think about. You just filled the sprayer with Roundup, and you went to spray whatever needed to be sprayed. Simplicity was the greatest thing about it. Didn't even have to think.

A father and son collaborating on an Illinois farm made the significant savings of managerial resources allowed by HT technology abundantly clear:

> Son: I hate to make this statement—take it for what it is—but Roundup made the farmers that weren't necessarily good on the things they should have been doing, it made them look like good farmers.
>
> Father: It forgave a lot of mistakes. Son: That's a good way to put it.

3.2.2. Changes in Fixed Capital: Farm Size and Equipment

The interviewees made it clear that GT technology's management resource savings and increased time flexibility not only provided the seasonal crop benefits described above, but also triggered changes over time in farmers' decisions about fixed assets, lowering the demand for mechanical weed control equipment. In addition, almost all of the interviewees speculated that the flexibility and simplicity of using GT crops permitted farmers to expand their acreage and manage larger farms. One farmer stated,

> Yeah, I think that has definitely allowed the big guys to get bigger, sure. Because they go in and they plant, and then spray, and then harvest.

However, the causality between GT crop adoption and increases in farm size is difficult to determine; many factors influence farm size. In theory, technological change may affect farm size through two channels: by allowing economies of scale of crop production (that is, by lowering the per-unit costs of output expansion) or through labour saving—that is, by reducing the labour needed for any given production quantity. Agricultural economists tend to judge the labour-saving aspects of technological change to be the more important. MacDonald, Korb, & Hoppe (2013) presented empirical evidence of time savings from GT technology, which they cite as playing an important role in the consolidation of crop farms since 1995 along with other technological changes such as larger farm equipment and faster tractors, as well as costs savings from new information technologies.

3.2.3. Development of Weed Resistance to Glyphosate

Soon after the introduction of HT technology, the industry producing glyphosate and HT seed frequently claimed that the HT system was different from selective herbicide systems in that biological resistance to HT technology would not evolve. For example, Bradshaw, Padgette, Kimball, & Wells (1997), all employees of Monsanto, claimed that "*the complex manipulations that were required for the development of glyphosate-resistant crops are unlikely to be duplicated in nature to evolve glyphosate-resistant weeds*" (see Bonny (2016), for other examples). This claim falls under what sociologists have coined "the economics of techno-scientific promises” (Joly, 2010). As an academic researcher we interviewed opined:

> Many people drank the Kool-Aid that Monsanto was serving that said, “Oh, this is a really complex way that the glyphosate kills weeds, so resistance will never evolve.” They forgot to read Darwin and Wallace.

Indeed, the initial claims that resistance would not develop were wrong. Currently, three weeds are displaying significant glyphosate resistance in Midwest fields: tall waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer), giant ragweed (*Ambrosia trifida* L.), and marestail (*Erigeron canadensis* L.).

Given that weed susceptibility to glyphosate is a common-property resource among farmers (as weed resistance may diffuse spatially via weed seeds or pollen), even if they had been aware from the start of the risks of resistance, farmers would not have had individual incentives to develop management strategies to delay it. The current aggregate farm structure also makes it difficult for farmers to cooperate with each other; interviewees told us that current farms are sometimes so large, with fields of single farms spread out over as much as one hundred miles, that producers may not even know their neighbours, and compete to rent or buy land. Additionally, most Midwestern farm land is rented, and growers who do not own their land have less incentive to account for the long-term development of resistant weeds. Several interviewees also highlighted farmers’ faith in technology and their beliefs that either companies will offer new solutions or old solutions will work again:

> Farmer. I think there’s always going to be a chemical to kill certain things.
> Interviewer. You think the industry can develop new chemicals if we come to that?
> Farmer. Oh yeah, I’m sure they can. Some of the older chemicals we may not be able to use anymore because weeds are tolerant to them. If you have a certain chemical that does not kill a weed anymore, you go to a different chemical, and if that one does not kill it anymore, you come back to another chemical. There’s always a circle that if you wait long enough it will do it again.

In contrast to the regulation of insect-resistant *Bt* crops, which imposed a mandatory refuge policy from the start to manage resistance in target pests, no regulation has been established for HT crops even though the topic was briefly considered in House hearings in 2010 (US House Committee on Oversight and Government Reform, 2010). Our interviews highlighted several reasons for regulatory differences among genetically modified crops. First, the regulatory context is different: contrary to *Bt* crops, GT crops contain no toxin added by genetic engineering at which regulation could be aimed. Furthermore, the EPA determined that because *Bt* crops lowered pesticide use, *Bt* susceptibility was a public good. In contrast, the perception was that GT crops were introduced to simplify growers’ lives, rather than decrease herbicide use. Additionally, different EPA divisions regulate *Bt* crops and HT crops, and there was little internal push for regulation of the latter. Furthermore, whereas entomologists were actively pushing for a public strategy to establish refuges, weed scientists were more focused on weed control than weed ecology and, by and large, did not call for HT crop regulation. Finally, providing incentives to farmers to create refuges for *Bt* crops can be relatively simple. No equivalent simple policy has been identified to manage the development of weed resistance; IWM solutions are more complex and more costly to implement, and they vary depending on the specific context. The EPA has recently developed guidelines on resistance development for pesticide labels and educational materials for farmers (U.S. EPA, 2017a, 2017b). However, the EPA is not contemplating mandatory policies, which would be more likely to have a sizeable influence on the evolution of weed resistance.

3.2.4. Current Tools to Fight Resistant Weeds

The current strategies for controlling glyphosate-resistant weeds are mainly herbicide-centric, and they include increasing doses of glyphosate, supplementing glyphosate with other herbicides, and using transgenic dicamba- or 2,4-D-resistant crops.

Glyphosate- and dicamba-tolerant Roundup Ready Xtend™ soybeans were commercialized in 2017. Enlist™ or Enlist Duo™ soybeans and corn, tolerant to 2,4-D alone and to 2,4-D and glyphosate, respectively, were commercialized in 2018 (after our interviews). The adoption rate of dicamba-tolerant soybeans in the U.S. was approximately 20% in 2017.[1] Our interviews indicated that many farmers judge dicamba to be less effective than glyphosate because dicamba does not control grasses and is ineffective on large weeds. In addition, because of dicamba's tendency to drift to neighbouring farms, in 2017 several of the interviewed farmers avoided these crops for fear of problems with neighbours. As summarized by an interviewed academic, the more fundamental problem is that weeds will evolve resistance to dicamba:

> Both of those, the 2,4-D and the dicamba, are relatively old products—some of the oldest. They haven't had widespread usage and so the level of evolved resistance to those herbicides is quite low, so they are like maybe a band-aid for a short period of time. But it is still a system based on herbicides.

Application of herbicide mixtures might mitigate the evolution of weed resistance, as long as resistance to the active ingredients has not already evolved, but resistance mitigation would exacerbate health and environmental costs. An academic interviewee stated,

> I think the industry's approach to it—and I have misgivings about this—is that we throw on more herbicides. If you get a new herbicide coming to the market now, it's always a two-or three-way mixture of different herbicide active ingredients, with the hope that if I have enough tools in the jug, then I'm going to be able to manage that problem. The negative to me from that is that we are using more pesticides than we were before, which has environmental implications. But if you look at the models, it's probably the smartest way to approach the resistance problem because weeds are less likely to survive a mixture than a single active ingredient.

It is possible to complement the chemical control of resistant weeds with mechanical control, including one or possibly two pre-plant tillage passes (one in the early spring and the other immediately before planting, to control emerged weeds). Several farmers had begun using

[1] See https://extension.psu.edu/looking-back-at-xtend-soybean-and-changes-for-2018.

their old interrow cultivators again on localized parts of their farms where resistant weeds were problematic. However, the relatively small sizes of the old cultivators greatly slowed the production process. For example, one farmer explained that he had cultivated a few acres with an old, six-row cultivator even though his newer planter could cultivate 16 rows. Therefore, more time was consumed cultivating six rows up the field, six rows back, and then four rows up again. Contemplating the effort required to cultivate more than the marginal areas he had cultivated that year, he remembered the consequences of cultivating as a younger farmer:

> My hearing is bad because of that cultivation. […] It was no fun, and it took the whole summer up. Just a pain.

There is currently no significant IWM adoption in the U.S. Midwest. Farmers overwhelmingly consider IWM to be insufficiently effective, and too complex, time consuming and costly. An academic interviewee provided an apt summary:

> Herbicides work, for the most part. They're inexpensive, it's easy. Doing something like rotating crops would help reduce the number of weeds, but it would not completely take care of weeds. You still would need herbicides, probably. "I can rotate and spray, or I can just spray. So I just spray." The other available strategies require multiple strategies to be completely effective. You could do lots of things to get there, or you could do one thing: spraying herbicides.

3.2. Barriers to IWM

Given the negative externalities of herbicides, the inevitable development of weed resistance, and that no new herbicide modes of action seem to be in the research and commercial pipelines, the future methods and costs of weed control are worrying. Below, we discuss additional difficulties producers face when transitioning to IWM.

3.2.1. Possible Barriers to Crop Rotation

Although IWM is a combination of several practices, the consensus from our interviews was that

> [crop rotation is] the single most important strategy that it would be nice if we do more of,

and that

> true IWM has to start with a good crop rotation; otherwise, you're forcing the chemicals to do all the work.

Longer crop rotations would be especially beneficial for corn and soybeans, given that they have similar planting dates, shared weed problems and corresponding shared herbicide strategies. However, there was a consensus among the interviewees that bringing additional crops into the current corn-soy rotation is currently "*not really an option*," as corn and soybeans thrive in Midwestern growing conditions. As underlined by Liebman, Mohler, and Staver (2001)

(p. 191), larger farms are less suited for ecological weed management. Thus, increasing farm sizes have reinforced the efficiency of herbicidal weed control. Through our framework, we can interpret this as coming from differences in profitability and being exacerbated by lock-in. First, herbicides have made the removal of oats and alfalfa from rotations possible, which has further encouraged farm specialization in field crops and widened the disconnection between crop and animal production. Reintroducing these crops would be difficult in the current situation, as they are no longer compatible with the internal structure of farms without animal production—which is a type of switching cost. The absence of local markets for wheat, oats, and alfalfa also complicates the access to inputs suited for their production, and severely limits the ability of farmers using IWM to deliver their crops to local buyers; this is an indirect network effect. Cover-cropping could complement herbicidal weed control, but it is complicated, and increases weather-related risks.

Corn and soybean production are incentivised by two principal government policies. First, the Renewable Fuels Standard mandates that the petroleum industry mix a minimum proportion of crop-based ethanol into the nation's gasoline supply (U.S. EPA, 2018). As a result, approximately one-third of the nation's total corn production went to the production of ethanol in 2016 (U.S. Department of Energy, 2018). This government-mandated demand for corn increases the world price of corn relative to that of other crops and thus encourages corn production. Second, subsidized crop insurance is the principal instrument used by the U.S. government to supplement the incomes of farmers in the corn-soybean belt. To some extent, the programme incentivises monocultural agriculture simply because it increases the already existing competitive advantage of corn and soybean production to that of other crops likely to be used in longer-term rotations in the U.S. Midwest. Crop insurance subsidies cover some small rotation crops—oats, for example—but not others, such as alfalfa (Zulauf, Schnitkey, Coppess, & Paulson, 2018). We can conjecture about a policy persistence effect: there have been relatively few regulatory obstacles to simplifying crop rotations; farmers' current assets are compatible with herbicidal weed control in corn-soy rotations, making it more difficult politically to increase regulatory obstacles to herbicide development and use.

3.2.2. Possible Barriers to Interrow Cultivation

Our interviews resulted in detailed discussions about the use of interrow cultivation for weed suppression. Cultivation was discussed more as a complement to herbicide-centric weed control than as a component of IWM. The general thought expressed was that weed resistance may now be making such cultivation necessary, much as it was a necessary complement to selective herbicides prior to the adoption of HT crops. However, the barriers to interrow cultivation present a general difficulty for IWM practices beyond this specific case. This definitive answer came from a farmer when asked whether large-scale mechanical weed control would be an option in the case of resistance build-up:

> No … [laughs] I don't think we'll ever see that again!

This response may be attributed to a switching cost resulting from increases in farm size, which has created incompatibilities with interrow cultivation. Currently, the equipment industry lacks incentives to develop more efficient cultivators than the old ones still owned by some farmers, which creates an indirect network effect for a farmer who would want an efficient cultivator but cannot buy one because of a lack of general market demand. No doubt manufacturers could respond quickly to an increase in cultivator demand. Cultivators are relatively simple machines, manufactured at relatively low costs. However, cultivating 24 rows at a time would be challenging because the wider cultivator makes it more difficult to avoid digging up the crop along with the weeds. Interrow cultivation is also not very compatible with no-till methods, which can complement HT technology.

Our interviewees told us that a sprayer can be driven at fifteen miles per hour across the fields, allowing the farmer to cover a number of acres very quickly and with little difficulty. Field cultivators typically must be driven from five to seven miles per hour, and the work is exacting; the driver must pay constant attention to the action behind him to avoid digging up the crop with the weeds. Of course, the costs of the farmer's cultivation time and efforts might be defrayed by hired labour. However, our interviewees stressed that the pool of labour capable of cultivating efficiently and willing to take on the work is quite limited in rural Midwestern labour markets.

Considering the discussion above, the prohibitive costs of interrow cultivation are not the fixed cost of buying new machinery, but rather the variable costs of the slow task of cultivation. An academic summarized the situation:

> I can spray a field much faster than I can cultivate it.

While the cost of labour is exogenous to the dynamics of weed control and therefore not a factor in lock-in, the price of herbicides and thus the relative costs of labour and herbicides are possibly affected by the policy persistence of regulations encouraging herbicide use, as discussed before. This topic was beyond the scope of the interviews.

3.2.3. Possible Barriers in Terms of Knowledge

Another important barrier to large-scale IWM is the path dependence of innovation. Almost a generation of farmers have now farmed with GT crops, and know-how about selective herbicide management and field scouting is fading. However, our interviewees believed that knowledge of pre-GT practices has not yet completely disappeared and, though less accessible, is still available from land-grant universities and extension services, via the Internet, and through traditional communication outlets. Of course, the U.S. is reducing its public R&D in the agri-food sector—a general trend that is largely exogenous to the dynamics of weed control. This public investment has decreased both in absolute terms and relative to private research; the expenses of agri-food R&D are now double the expenses of public R&D (Pardey, Chan-Kang, Dehmer, & Beddow, 2016). Farmers have begun substituting public extension services with services from private crop consultants and input retailers.

Midwestern farmers' knowledge of IWM practices was limited even before the advent of

GT technology; very few farmers chose IWM over selective herbicides. Nor has IWM been the focus of academic weed science, which has traditionally been herbicide-centric in its research and funding (Davis et al., 2009; Shaner and Beckie, 2014). Private companies now conduct a larger share of agri-food R&D than do public institutions, and they have greater incentive to investigate herbicide-centric rather than non-herbicidal weed control strategies. For example, current cover-crops research is primarily public; supply companies make scant profits selling cover crop seed. There is also inertia in research: there are sunk costs, and there is an incentive to exploit past investments in specific intellectual capital.

4. Discussion and Conclusion

Our analysis has highlighted that the current dominance of herbicide-centric weed control in crop farming in the U.S. Midwest is unlikely to fade any time soon in favour of a more sustainable form of agriculture relying on IWM. Indeed, IWM adoption faces high barriers to entry, including barriers to crop rotation, interrow cultivation, and knowledge acquisition. Some of these barriers seem mostly exogenous to the dynamics of weed control. First, corn and soybeans thrive in the agricultural conditions of the U.S. Midwest, reducing private economic incentives for other rotations. Second, the high cost of qualified rural labour hampers the adoption of more time-consuming IWM practices. Third, the increase in the relative share of private agri-food R&D compared with public R&D may decrease the incentives for IWM research because of low appropriability.

Other barriers, however, are at least partly endogenous to the dynamics of weed control; they feature various self-reinforcing effects that contribute to the lock-in of herbicide-centric weed control. These lock-in effects help maintain the herbicide-centric path of weed control dynamics despite another externality at play, which is the common-pool nature of weeds and of weed susceptibility to herbicides. This common-pool nature contributes to the decrease in herbicides' effectiveness over time as weed resistance develops. The negative externalities of herbicides on health and the environment make this path problematic.

We have identified four types of self-reinforcing effects. First, incompatibilities of IWM practices with the current size of farms and farm machinery create switching costs. Existing machinery, such as the interrow cultivators made unnecessary by GT technology, are ill-suited for use with today's larger machinery. Farm size is enhanced by the availability of herbicidal weed control; the large size of farms makes it difficult to adopt IWM practices, which tend to be labour- and management-intensive processes. Second, indirect network effects have resulted as chemical herbicides have contributed to the simplification of crop rotations, which no longer include fodder crops; this simplification has fostered the specialization and separation of field crop farms and livestock farms. The reintroduction of fodder crops on grain farms lacking livestock production would be challenging, and transporting fodder crops to livestock-intensive areas is expensive. Third, there is path dependence in R&D. IWM has never been the main focus of weed science. Fourth, the U.S. biofuels mandate and subsidized crop insurance programmes encourage corn and soybean production, and therefore discourage longer crop rotations. Although it was not specifically addressed in our interviews, the policy persistence of regulations pertaining to the market authorization and use of herbicides probably also plays a role in the current price of herbicides and the high cost-effectiveness of herbicides compared with labour.

The lock-in effects that we have described do not result from GT crop adoption alone but also more generally from the much longer path of herbicidal control. GT crops may have reinforced this herbicide-centric path by encouraging increases in farm acreage and machinery sizes, but the trends of larger farms and equipment were already in play long before the advent of GT crops.

The prospects of whether herbicide-centric weed control will still dominate in the long run may depend on two factors. First, it will depend on whether agrochemical companies manage to develop new herbicide compounds as weed resistance to current herbicides increases. Second, increased knowledge and citizen awareness of the negative health and environmental impacts of herbicides could create political leverage to change farm policies, pesticide authorization procedures, and policies to support the development of alternative cropping systems, thus changing the incentives faced by farmers to so predominately rely on herbicides for weed control.

We have provided a qualitative description of the dynamic effects at play in the path of GT crop adoption in the U.S. Midwest. Our economic analysis of the effects of the adoption of farm innovations has shown that dynamic relationships exist between weed management choices and choices about fixed farm assets such as land and equipment. It is therefore important to account not only for the variable costs at the field scale but also for the market-scale structural transformations brought about by these innovations. This study also underlines the interest in comparing the effect of an innovation (for example, GT crops) not only with the dominant technology in place (in our case, herbicidal control) but also with more sustainable alternatives (such as IWM) that have beneficial effects on health and the environment.

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