Explaining Growing Glyphosate Use:

The Political Economy of Herbicide-Dependent Agriculture

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Highlights:

- Global glyphosate use in agriculture has increased sharply since the 1980s
- There are growing concerns about the environment and human health implications of glyphosate
- The interplay of technology, market and regulatory forces encouraged expansion of glyphosate use
- Four distinct yet overlapping configurations of these forces have emerged since the 1980s

Abstract:
The growing use of chemical herbicides for weed control has become a dominant feature of modern industrial agriculture and a major environmental and health concern in agricultural systems worldwide. The paper seeks to explain how and why glyphosate-based agricultural herbicides have become so entrenched in modern agriculture. It finds that a complex interplay among technological, market, and regulatory developments have encouraged a lock-in of glyphosate linked technologies in agricultural systems. These are: (1) the repurposing of glyphosate for use with genetically modified crops; (2) the rise of the generic glyphosate market which globalized the chemical's use and encouraged new agricultural uses; (3) new technologies such as digital agriculture and genome editing that interface with glyphosate use; and (4) growing corporate market power and declining public investment in agricultural research programs that constrained innovation in non-herbicide technologies.

Keywords: Glyphosate; agriculture; technological innovation; corporate power; regulation; herbicides

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I. Introduction

The growing use of chemical herbicides for weed control has become a dominant feature of modern industrial agriculture, and a major environmental and health concern in agricultural systems worldwide. The use of glyphosate, the most widely applied herbicide globally, has increased by a factor of 15 from 1996-2014 (Benbrook 2016). It is really only in the past 70 years that chemical herbicides came into widespread use as key components of modern industrial agriculture, and glyphosate, developed by the agricultural input firm Monsanto, has only been on the market since the mid-1970s. Although many analysts and most governments consider glyphosate to be to be a relatively safe herbicide compared to other chemical herbicides that are more toxic, there is growing public concern about the consequences of its increased application in agriculture. Numerous problems associated glyphosate use have sparked considerable political debate in recent years, including: the spread of glyphosate-resistant weeds, health concerns about exposure either from occupational use or from residues found on commonly consumed foods, and its broader environmental effects on biodiversity, water and soils. As these concerns mount, a growing number of governments around the world have taken the step of implementing restrictions on its use, even as the corporations that produce glyphosate-based herbicides insist that their products are safe. The process of regulating glyphosate has been highly contentious in most cases, and in some instances, restrictions have been delayed or rolled back, signaling the extent to which glyphosate is embedded in agricultural systems.

Effective policy responses to growing concern about glyphosate requires a deeper understanding of how it came to be so entrenched, or ‘locked-in’, as a key agricultural input in the first place. The existing literature offers only partial answers to this question. Although there is a burgeoning literature on glyphosate, most of it is scientific in nature, focused on its human health and environmental impacts (Duke and Powles 2008; Kuhra et al. 2016). An emerging social science literature has focused mainly on legal and policy aspects of re-registration as concerns about its safety have mounted (Tosun 2019; Székács and Darvas 2018) or social movement responses to its impacts (Bain et al. 2017; Lapegna 2016). Many studies note the rise of agricultural biotechnology as a key factor behind growing glyphosate use (e.g. Benbrook 2016; Bonny 2016). This paper makes the case that while agricultural biotechnology is certainly a key piece of the explanation, it is only part of the story of glyphosate’s increasingly central role as an agricultural input. I argue that a fuller explanation requires a consideration of how technological change – including but not limited to the rise of agricultural biotechnology – interacts in complex ways with market conditions and the regulatory environment. In other words, the technological innovations that gave glyphosate such a prominent role in modern industrial agriculture did not occur in a political or economic vacuum. If we want to understand how glyphosate has taken such a prominent role in modern industrial agriculture, we need a deeper appreciation for the political and economic context in which those technologies were developed and diffused.

The paper adopts an eclectic international political economy (IPE) approach, which is inspired by the work of Susan Strange who argued it is essential to examine changing dynamics between states, markets, and technological developments if we want to understand shifting power relationships in the global economy that matter for politics (Strange 1996). Strange noted that technological change is often an overlooked factor in the shifting balance of power between states and markets (1996, 7). I supplement this state-market-technology framework with insights from International Political Economy and Environment (IPEE) literature that examines the relationship between broad structural trends in the global economy, including the exercise of corporate power, and its implications for the environment (Levy and Newell 2005; Clapp and Helleiner 2012). This literature includes earlier IPEE work on the forces driving the development and global deployment of agricultural biotechnology, which incorporates analysis of some of the same firms as well as some of the technologies that are part of the glyphosate story (Newell 2006; Williams 2009). The analysis also draws on insights from the literature on the interface of technological lock-in and environmental outcomes, which highlights the ways in which economic and social conditions can create path dependencies by reinforcing one technologies while constraining innovation in others, even when dominant technologies have known environmental disadvantages (Arthur 1989; Seto et al. 2019).

Drawing on data from industry reports, government documents and scientific papers, the analysis reveals a number of distinct yet overlapping configurations of technology-market-state regulatory forces that have successively emerged over the past 50 years, each of which has a specific dynamic, or interplay, that contributed to putting glyphosate, and herbicides more broadly, at the center of modern agricultural practices. In each of these configurations, economic conditions, government regulatory frameworks, and technological change interacted in complex ways to create incentives for further glyphosate use. These are: first, the repurposing of glyphosate for use with crops that are genetically modified to be tolerant to herbicide applications; second, the rise of the generic glyphosate market which contributed to its worldwide spread and spawned new glyphosate practices; and third, the rise of new digital technologies, including digital farming and genome editing, that seek to bring more precision to glyphosate applications as a means to address concerns about its safety. Each of these configurations encouraged an increase in agricultural glyphosate use. Alongside these dynamics, a fourth configuration of these forces emerged and intensified over the past fifty years which worked to constrain innovation in both chemical and non-chemical modes of weed control. This dynamic is characterized by growing market concentration and power in the agricultural input sector accompanied by a stepping back of the state's role in agricultural research and development that resulted in limited investment and innovation in alternative weed control technologies.

This analysis adds to the existing literature by providing a deeper understanding of the complex and layered forces – technological, market, and regulatory – behind the dominance of glyphosate in particular and the herbicide-centric agricultural model more broadly. It also adds to earlier work on the political economy of agricultural biotechnology that drew connections between market imperatives of powerful transnational firms on one hand, and policy on the other, as key forces behind the expansion of biotechnology (Clapp 2003; Newell 2006; Glover 2010; Wield et al. 2010). That earlier work, however, was focused mainly on seed technologies rather than herbicides. This paper analyzes the various configurations of these forces as they played out in subsequent years with respect to herbicide use specifically.

II. Chemical Herbicides in Agriculture and the Problem with Glyphosate

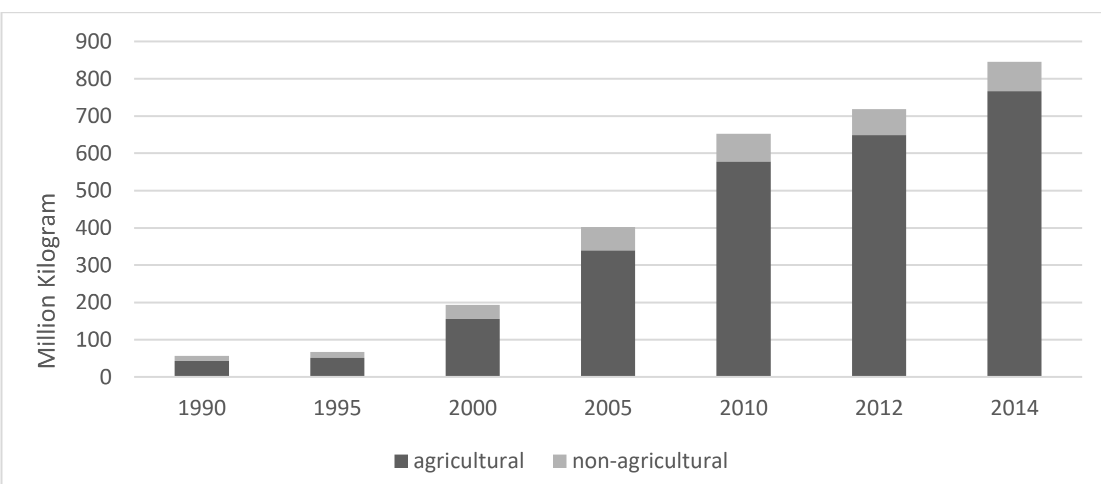
Historically, farmers used a range of methods for weed control. Mechanical weed clearing, such as the use of hand implements and plow tools for dragging weeds out of the soil, was a dominant approach to weed control until the 1940s. In the mid-1800s, farmers began to use inorganic compounds – such as salts, sulfur compounds, and lime – to kill weeds. From the early 1900s to the late 1930s, some farmers used arsenic based compounds to tackle weed problems, despite their highly toxic properties. In the 1930s, farmers also experimented with other weed control strategies, such as use of electricity and flames (Timmons 2005). Although tractors were increasingly adopted in the US from the early 1900s, it was not until after the mid-1940s that tractor technology improved enough for effective mechanical weed control (Swinton and Van Deynze 2017, p.563).

It was only from the mid-1940s that organic chemical compounds began to be deployed as agricultural herbicides, coinciding with more widespread tractor use which enabled their application across larger areas. The first modern chemical herbicide was 2,4-D, which was discovered and synthesized as an herbicide in the early 1940s, and widely commercialized after 1945. Other chemical herbicides, including atrazine and dicamba, were developed and marketed widely in the 1950s and 1960s. These chemicals were successful in killing unwanted plants over wide areas and were popular because they saved labor. As farm size began to grow with the increasing mechanization of agriculture in the middle of the 20th century, herbicide use expanded dramatically and became the norm for weed control (Osteen and Fernandez-Cornejo 2016).

Glyphosate was first introduced as a commercial herbicide for agricultural applications in the mid-1970s. A Swiss pharmaceutical company first synthesized the glyphosate molecule in 1950, although it did not identify any useful applications for it and subsequently sold it to other firms (Benbrook 2016, p.1). The chemical firm Monsanto discovered that glyphosate could be utilized as an active ingredient in herbicides in 1970, and by 1974 the firm had begun to commercially market Roundup, a glyphosate-based herbicide. From early on, glyphosate was widely considered to be a "perfect herbicide" because it was highly effective and widely deemed to be less toxic than other chemical herbicides (Duke and Powles 2008, p.319). Glyphosate is non-selective and was hence used largely to kill weeds in fields prior to planting, or after harvest to clear fields, to ensure that it did not damage crops (Benbrook 2016). Glyphosate was just one of many herbicides on the market from the mid-1970s-mid-1990s – including atrazine and dicamba – that could serve this function.

Glyphosate use was marginal in agricultural applications through the late 1980s and early 1990s as it competed with other herbicides on the market. However, by 2015, it had become the world's most widely used herbicide, with global applications increasing 15-fold from 1990-2014 (Benbrook 2016), as shown in Figure 1. This rapid increase in use can be illustrated by looking at the extent to which it was used on four major crops in the US – corn, cotton, soy, and wheat. Glyphosate accounted for 1 percent of herbicides sprayed on those crops in 1982, climbing to 4% in 1995, 33% in 2005, and 40% in 2012 (Osteen and Fernandez-Cornejo 2016, p.4). It is notable that although herbicide use overall in the US, for example, increased sharply from the 1960s to early 1980s, it leveled off until around 2005, and in this period the increase in glyphosate largely replaced the use of other herbicides. After 2005, herbicide use overall rose sharply again, alongside rising glyphosate use (Nehring 2019).

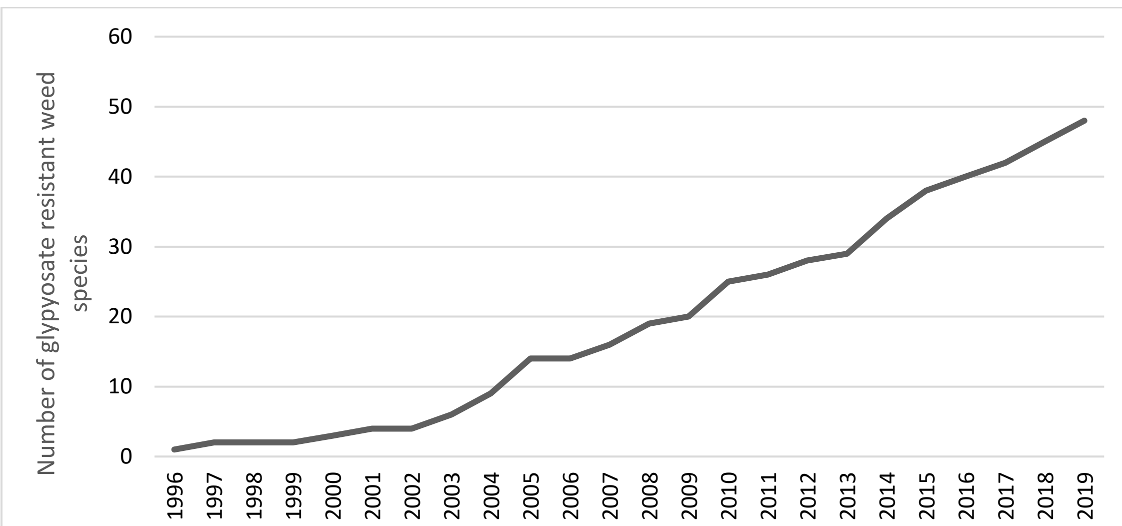
Figure 1: Global Glyphosate Use, 1990-2014



Source: Benbrook 2016

As glyphosate use soared, particularly in North America, a number of problems associated with its use also grew (Davis and Frisvold 2017). One of the first problems to arise was the development of glyphosate resistant weeds, the product of greater use in general as well as back-to-back use in successive crop rotations. Currently, there are over 250 weed species across 70 countries that have evolved to be resistant to at least one type of herbicide (Heap 2020). This figure includes at least 48 weed species (as of early 2020) that are resistant to glyphosate, as shown in Figure 2. In the face of growing weed resistance, farmers initially sprayed glyphosate in higher amounts on the same crops to control those weeds. As glyphosate-resistant weeds continue to emerge, farmers, encouraged by herbicide companies, are increasingly applying older and more toxic chemicals, such as dicamba and 2,4-D, to control weeds in their fields (Bain et al. 2017).

Figure 2: Increase in Glyphosate-Resistant Weeds Globally, 1996-2019



Source: Heap 2020.

Concerns have also mounted over the toxicological effects of glyphosate, in particular the health effects of human exposure to the chemical. Initially, glyphosate was widely considered much safer than older herbicides like atrazine or dicamba (Duke and Powles 2008). However, with growing use of glyphosate over the past 25 years, there have been growing concerns about its impact on human health, in particular its connection to non-Hodgkin's lymphoma, a type of cancer. A large number of studies have examined this question (Torretta et al. 2018), and in 2015, a study by the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) declared that glyphosate was 'probably carcinogenic' (WHO 2015). This finding set off a heated debate over the toxicological profile of glyphosate, with many industry-sponsored studies challenging the studies that identified risks with the chemical (Krimsky and Gillam 2018).

There has also been an uptick in attention to the potential health effects of glyphosate residues that are increasingly being detected on commonly consumed food items (Myers et al. 2016; Xu et al. 2019) and in drinking water supplies (Noori et al. 2019). While many of the studies on dietary and environmental exposure to glyphosate indeed detect glyphosate residues, and some studies have detected the chemical in the urine of both humans and animals, there is enormous controversy over whether the levels detected are cause for concern (Solomon 2019). In Canada, for example, the Canadian Food Inspection Agency found that nearly 30% of samples of over 3000 foods it tested contained glyphosate residues (CFIA 2017). While most of these residues were below the maximum recommended limit, nearly 4 percent of grain products exceeded those limits (CFIA 2017).

Scholars have studied the impact of widespread glyphosate use on the environment more broadly as well. One recent study, for example, shows that glyphosate-based herbicides threaten biodiversity because they are toxic to a variety of aquatic organisms and harmful to soil microflora, while herbicide-based agriculture more broadly contributes to a decline in wild plants (Schütte et al. 2017). Glyphosate run-off from plants and soils has also been identified as a culprit in contributing to high phosphorus loads in aquatic ecosystems (Hébert et al. 2019).

As this brief review shows, the growing reliance on glyphosate-based herbicides in agriculture over the past 50 years has spawned numerous concerns about its impact on agricultural productivity, human health, and the environment. As herbicides have become central to modern industrial agriculture over this period, these problems have become some of the biggest challenges facing that model of agriculture today. The remainder of this paper examines driving forces behind this growing reliance on glyphosate.

III. Forces Encouraging Increased Glyphosate Use

To gain insight into how glyphosate became so entrenched in modern agriculture, it is helpful to unpack the forces that encouraged the development of new technologies designed to work with it as well as broader incentives that encouraged its diffusion and uptake in agricultural systems. Such an analysis requires an examination of the dynamic relationships between market trends, state policies and regulations, and technological developments associated with glyphosate. Examining these relationships in a global context is important, because glyphosate is utilized in many countries around the world, and transnational agribusiness firms are key actors in developing and marketing glyphosate and other agricultural technologies that are designed to be used with it. Analysis of these relationships over the past 50 years reveals multiple distinct configurations of a dynamic interplay between technological, market, and regulatory forces in ways that worked to reinforce glyphosate use, creating path dependencies that locked it in as a key mode of weed control. These distinct configurations interacting forces first emerged in different timeframes, but have overlapped with and reinforced each other over time. This section outlines three configurations that were explicitly tied to technological developments and incentives for greater glyphosate use, while Section IV outlines an additional configuration of forces that discouraged innovation in alternatives to glyphosate.

The Repurposing of Glyphosate with GM Crops

The introduction of genetically modified glyphosate-tolerant crops, first by Monsanto and subsequently by other large agricultural input firms which licensed the traits (Howard 2015), effectively "repurposed" glyphosate to be used in a new way, moving it from the margins to a new central role as a key agricultural input. This technological strategy did not just emerge simply as a result of scientific advances, however. The emergence of this technological innovation was deeply embedded in complex interplay of market and regulatory factors.

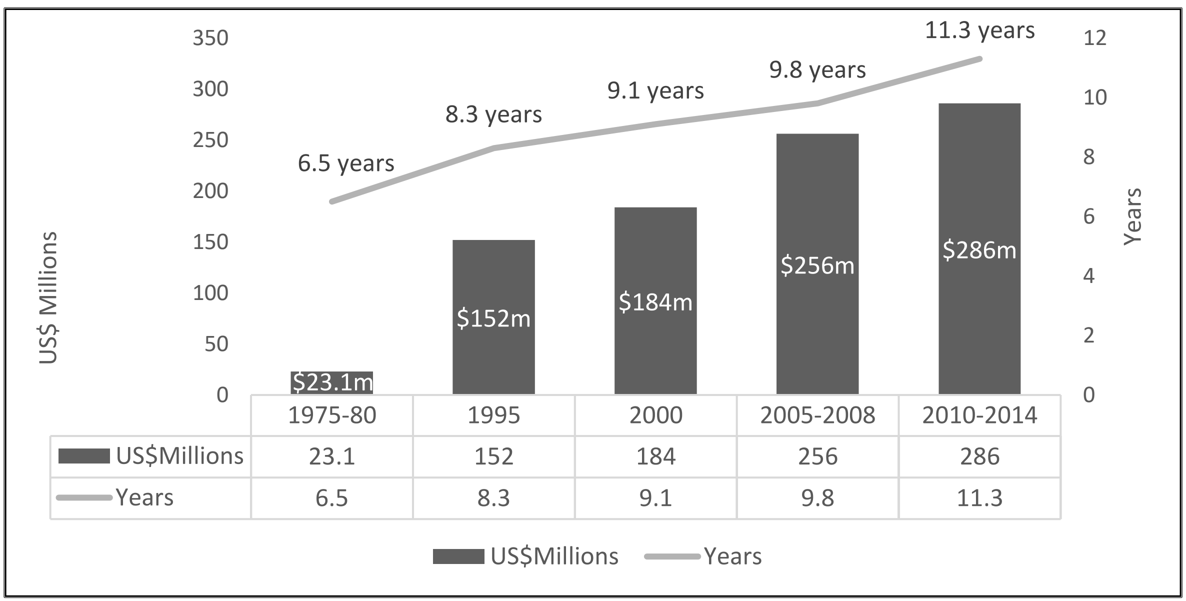
Agricultural input firms began research into agricultural biotechnology in the late 1970s and early 1980s in a bid to engineer plants to express new traits to improve agricultural performance, including for example traits for drought tolerance and insect resistance. From the mid-1980s, however, the most common trait that corporations pursued in practice was to engineer plants tolerant to the application of herbicides (ISAAA 2018). Monsanto developed the first genetically engineered herbicide-tolerant plant in 1987 – a soybean that could tolerate the application of glyphosate (Schneider 1990). Glyphosate was likely chosen as the chemical herbicide to tether to GM crops because, as noted above, it was widely viewed as being less toxic than other, older herbicides.

Whereas previously it would kill all plants, now glyphosate could be sprayed on genetically engineered glyphosate-tolerant crops to kill only the weeds, leaving the crops intact. That meant that farmers could now spray glyphosate not just prior to planting or after harvest to manage weeds, but also throughout the entire growing season without damaging the crop, saving labor that was devoted to weed control. Throughout the late 1980s and early 1990s, agricultural input firms introduced a range of glyphosate-tolerant crops – with the most dominant being soy, maize, cotton, and canola – the first of which was approved for commercial planting in North America in 1996. This technological innovation was a key development that fundamentally changed not just the way glyphosate was used agriculturally, but also the amount of the herbicide that was utilized by farmers.

The decision of agricultural input companies to introduce glyphosate-tolerant crops was in large part a response to market conditions in the agricultural input industry as well as the broader regulatory context. From the mid-1970s, it became more costly and cumbersome for industry to develop and market new active ingredients for herbicides. Growing environmental awareness of the toxicity of some agrochemicals at that time led many governments to require more testing prior to approving them for commercial use. The cost of developing new chemical herbicide products, for example, increased by a factor of six between 1975 and 1995, from US$23 million to US$152 million (Phillips McDougall 2016, p.35).

The amount of time it took to get new agrochemicals approved for commercial sale increased as a result of this new regulatory context. In the 1960s, for example, it typically took around 4 to 5 years to develop a new chemical and bring it onto the marketplace, while by the 1980s it took more than 7 years (Rüegg et al. 2007). By the mid-1990s, it took just over 8 years to bring a new agricultural chemical to market (including research, development, and registration costs), which typically began after a patent was secured on an active ingredient. Thus, this increased time-to-market effectively reduced the ability of firms to capitalize on their patent protection, which typically is 20 years in total (Ollinger and Fernandez-Cornejo 1995, p.16; Phillips McDougall 2016, p.4). The growing time and cost to develop new chemical herbicides (outlined in Figure 3) thus drove down profits in the sector throughout the 1980s and into the 1990s.

Figure 3 – Rising Costs to Develop and Bring a New Pesticide to Market, 1975-2014



Sources: Phillips McDougall 2016; US EPA 1978, p.39653 (time to market for a new pesticide, average 1975-1976).

By contrast, the cost of developing a new genetically modified crop and bringing it to market in the mid-1990s was around US$10 million – just a fraction of the cost of developing a new chemical herbicide (Ollinger and Pope 1995, p.56). The time it took to develop these genetically modified crops and bring them to market was also shorter, typically around 6 years in the mid-1990s (which itself was an improvement over the 10 years it typically took to develop plants that were conventionally bred) (Ollinger and Pope 1995, p.56). This cost and time differential between the development of herbicides and genetically modified crops, as illustrated in Table

1, helps to explain why the large agricultural input companies shifted the focus of their R&D programs from agrochemicals to seeds over the course of the 1980s and 1990s (Clapp 2003).

Table 1 – Comparison of costs to develop a new crop protection chemical and cost to develop a new genetically modified crop tolerant to existing herbicides, 1995

	R&D Costs	**Time**
New crop protection active ingredient	$152m	8.3 years
New genetically modified crop	$10m	6 years

Sources: Phillips MacDougall 2016; Ollinger and Pope 1995.

A further impetus for Monsanto to develop glyphosate-tolerant crops was that the patent for its glyphosate-based herbicide, Roundup, was due to expire in the US in 2000. By shifting to focus its technological innovation on developing genetically modified crops that could withstand being sprayed with glyphosate, the firm could ensure continued agrochemical sales alongside the sales of new genetically modified seeds even after the expiry of the glyphosate patent (Wield et al. 2010; Glover 2010). In fact, in the early years of marketing its new glyphosate-tolerant crops, Monsanto required purchasers of its seeds to also purchase Roundup brand herbicide, in a bundle (Dupraz 2012, p.223).

The corporate strategy of focusing on the development of genetically modified crops could not have been accomplished without a regulatory environment that allowed for the patenting of life forms, including plant genetic material. It was not until the mid-1980s, following important court decisions in the US, that intellectual property rights were granted for genetically engineered seeds (Sell 2009). The 1994 Trade Related Intellectual Property Rights (TRIPS) agreement of the WTO harmonized intellectual property protection across countries, requiring countries to adopt some form of IPR for plants and other life forms. Extensive lobbying by agricultural input companies for governments to adopt the TRIPS agreement demonstrated the interplay of market and regulatory forces (Newell and Mackenzie 2004).

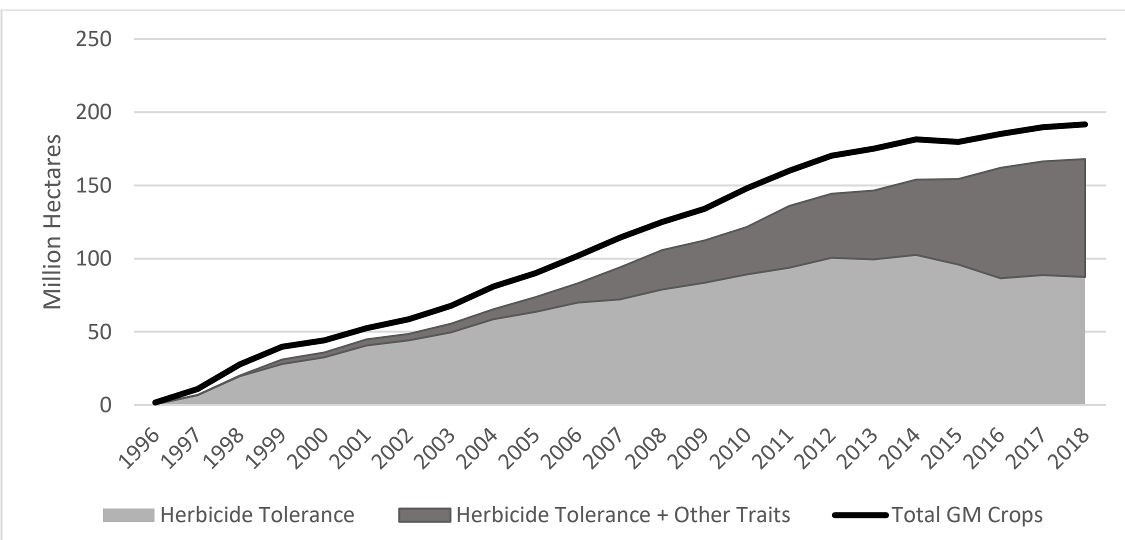
The firms in the sector also needed to acquire the capital and expertise to carry out this technological strategy. Throughout the 1980s and 1990s, large agrochemical companies began to merge not just with each other, but also with seed companies (Fernandez-Cornejo and Just 2007). The agricultural input companies also began to acquire biotechnology firms. As discussed more fully in Section IV, this concentration not only enabled these firms to develop genetically modified crops that were resistant to herbicides, but also discouraged innovation in other modes of weed control.

The Rise of Generics Spawns Global Spread and New Applications

In the early 2000s, a new configuration of technological change, market conditions, and the regulatory context began to emerge in ways that further encouraged glyphosate use. The approval of GM crops for cultivation in a growing number of developing countries, combined with the growing manufacture and sale of generic glyphosate formulations following the expiry of Monsanto's patent on glyphosate, led to a massive boom in glyphosate use that spawned new technological practices reliant on the chemical.

An increasing number of countries gave regulatory approval to commercially plant genetically modified seeds in the early 2000s, notably including Argentina and Brazil, both large agricultural producers. Although Argentina was among the early adopters of GM crops in the mid-1990s, its approvals of GM crop varieties increased sharply after 2000. Brazil did not approve GM crops for cultivation until 1998, and while its rate of adoption was slow at first, it took off after around 2003, surpassing even Argentina in 2009. Brazil's production of GM crops grew so fast that it soon became the second largest producer of these crops globally, trailing only the United States (ISAAA 2017, p.8). The vast proportion (approximately 80% or higher) of the GM crops (primarily soy and maize) under cultivation in Brazil and Argentina are glyphosate-tolerant varieties (ISAAA 2017). The total developing country area cultivated in GM crops surpassed the total industrialized country area by 2011 (ISAAA 2018). As shown in Figure 4, the proportion of GM crops grown globally that are engineered to be resistant to glyphosate (herbicide tolerant as a single trait, or herbicide tolerance combined with other traits) has consistently been more than 80% of the total since they were first introduced on the market.

Figure 4: Global Area of Biotech Crops 1996-2018 – total, herbicide tolerant traits, and herbicide tolerance + other traits.



Source: ISAAA data, https://isaaa.org/

At the same time that developing country acreage planted with GM crops grew, a growing quantity of inexpensive generic glyphosate came onto the market following the expiry of Monsanto's patent for the chemical in 2000. Monsanto continued to produce the majority of the world's glyphosate under its brand name Roundup, which it marketed as a premium version of the chemical at a higher price. The market for glyphosate became increasingly bifurcated over the course of the 2000s, with a growing number of generic firms entering the market and offering the chemical for sale at a lower price. Monsanto was able to maintain a significant market share by requiring farmers to use only Roundup brand of herbicide with their Roundup Ready glyphosate-tolerant crops in the early 2000s. Monsanto also actively pursued incentive programs with dealers, particularly in the US, that encouraged them to carry Roundup brand and not generic glyphosate products (Gillam 2017). If the dealers did not follow the practices mandated by Monsanto, they risked being dropped as suppliers (Khan 2013). The US Department of Justice pursued a complaint about these practices in 2007 as a potential violation of US anti-trust laws. Soon after, Monsanto backed off from these practices and the case was eventually dropped (Khan 2013).

Chinese glyphosate manufacturers upped their presence in the market in this period, especially when demand for glyphosate jumped in the aftermath of the 2008 food crisis, which led to a huge leap in investment in agricultural production to serve rising global demand for food, feed and biofuel stocks. The price of glyphosate rose in response to this demand, sparking major increase in generic production, primarily by Chinese firms. In 2008, the number of Chinese manufacturers producing the main ingredient for glyphosate tripled to 130 (Duan 2014), and by 2009 over 400 firms in China were producing glyphosate-based herbicide formulations (CNCIC 2009). Soon, the global market was flooded with glyphosate, leading to a sharp drop in price by 2010. Chinese manufacturers had significant cost advantages in production over the name-brand production from Monsanto. They faced lower labor costs, had readily available raw materials, and typically did not engage in their own innovative R&D. China produced at that time around 40% of the world's glyphosate supply, most of which was exported (Hilton 2012).

Low prices influenced uptake of glyphosate among farmers, particularly in the developing world. With Brazil and Argentina as the second and third largest producers of GM crops globally, South America became one of the biggest markets for agrochemicals, including glyphosate (Phillips McDougall 2018). Generic competition in some of the largest markets began to erode Monsanto's profit margins, as generic brands sold for one third less than the price of Roundup. In 2010, Monsanto cut the price of its brand name Roundup by half to compete (Hilton 2012). The result of these dynamics was that the price of glyphosate declined further in both segments of the market – brand name and generic – and its affordability thus increased for farmers just as they were expanding production to capitalize on higher world food prices.

These dynamics in the market encouraged other technology changes in the sector, including an increase in farmer uptake of no-till agriculture. No-till agriculture relies on herbicides to kill weeds in a field prior to planting, thus obviating the need to till the soil. Although no-till agriculture has been around for nearly a century, this practice increased dramatically in the early 2000s. In 1998, around 42 million ha of cropland were managed under no-till agriculture systems and by 2015 this figure rose to nearly 160 million ha (Kassam et al. 2019). Glyphosate is widely used in no-till practices on both genetically modified crops – such as soy, maize, and canola – and non-GM crops. Wheat and oats, for example, which are not genetically modified, are also increasingly being grown in no-till systems that rely on glyphosate spraying (Osteen and Fernandez-Cornejo 2016, p.3).

The use of glyphosate as a pre-harvest desiccant also began to expand from the mid-2000s as cheaper glyphosate herbicides came onto the market. In this application, farmers spray the chemical on crops in the field just prior to harvest to effectively kill the plant so that it can dry out fully to improve the efficiency of mechanical harvesting. The practice of crop is practiced mainly in northern Europe, Canada and in the northern United States, where weather conditions are wetter and the growing season shorter, making it more challenging for farmers to ensure that their crops have sufficient time to dry before harvest. Although there are other chemicals that can serve this function, glyphosate has increasingly been as a desiccant on both GM and non-GM crops, including wheat, barley, and oats, soy and other beans. Because the pre-harvest spraying occurs close to the time of harvest, this practice has led to higher glyphosate residues on crops when the reach the market, and thus residues on food products (Myers et al. 2016). Benbrook (2016, p.9) notes that Monsanto and other firms that are registered producers of glyphosate asked the US Environmental Protection Agency for, and were granted, increases in tolerance levels of glyphosate residues in key crops in this period. This example clearly illustrates the interplay between technological, regulatory and market actors with respect to this technological usage of glyphosate.

New Precision Technologies Reinforce Herbicide Centric Agriculture

A further configuration of technology-market-regulatory dynamics surrounding glyphosate emerged after 2015. These still unfolding dynamics have been shaped by growing contestation over glyphosate, with divergent policy directions in different parts of the world amidst growing economic liability of firms over its safety and pressure on both supply and prices of generic glyphosate. This context has encouraged new technological developments that both reduce glyphosate use in specific applications while reinforcing its overall role in agricultural systems.

In 2015, the International Agency for Research on Cancer (IARC), an agency of the World Health Organization (WHO), released a report based on a review of the available academic studies on the safety of glyphosate (WHO 2015). The IARC report concluded that glyphosate was “probably carcinogenic” based on findings of the studies showing higher rates of non-Hodgkin’s lymphoma among people with exposure to glyphosate compared to those who were not exposed. The IARC report was issued just as the European Union launched a review of glyphosate as part of its regulatory processes for renewing registration of the chemical for commercial use. Canada was due to re-evaluate glyphosate’s registration in 2017 and the US in 2019. Such reviews for re-registration typically occur every 10-15 years.

Given their strong commercial interest in the reregistration process for the chemical, it is not surprising that the large agricultural input companies responded aggressively to the IARC’s report on the toxicity of glyphosate. Monsanto allocated US$17 million for a public relations campaign to defend the use of the chemical (Gillam 2019). The firm insisted that glyphosate was safe (Monsanto 2017) and complained that the IARC reviewed only a certain subset of studies on its toxicity, mainly those that were not based on industry-sponsored research. The firm pointed out that the IARC study reached a different conclusion from those of many government regulatory bodies at that point and demanded that the IARC retract its report. The IARC has defended its study (IARC 2018), although the agricultural input firms continue to criticize it.

Monsanto actively sought to influence the regulatory decisions in the US, EU, and other countries regarding the chemical’s re-registration. For example, the firm arranged for its own scientists to ghost-write a number of academic studies without the published authors declaring their connections to the firm, and referencing these studies, pressured government regulatory agencies to approve the continued use of the chemical (see Krimsky and Gillam 2018). After its purchase of Monsanto was complete in 2018, Bayer continued to try to influence the regulatory environment when it published a 15 page document that simply listed quotes from ‘leaders’ that emphasize “glyphosate’s vital role in modern agriculture” (Bayer 2018).

The regulatory decisions on glyphosate in the EU, Canada, and the US, all eventually supported the position of the agricultural input companies that the chemical was safe, and it was approved for use in all three jurisdictions, although in the EU the approval was limited to a period of five years (until Dec. 2022) while further evaluation took place (Tosun et al. 2019). In each of these regulatory decisions, the evaluation included a review of the available studies on the safety of glyphosate, but unlike the IARC review, they did consider the industry-sponsored studies in their assessment (Benbrook 2019). It was later revealed that the EU decision was based on an assessment report that had plagiarized sections on health risks from industry reports (Nelson 2019).

But even as the EU, US and Canada approved glyphosate for re-registration for agricultural use, a number of other countries and jurisdictions began to put restrictions in place on the use of glyphosate, largely in response to the IARC report's findings.[1] In 2016, six countries of the Gulf Cooperation council – Saudi Arabia, Kuwait, the United Arab Emirates, Qatar, Bahrain, and Oman – were among the first countries to put national bans in place on the use of glyphosate for any purpose. St. Vincent and the Grenadines banned the import of glyphosate in 2018, and Vietnam banned glyphosate use in early 2019. Luxembourg announced plans to ban glyphosate by the end of 2020, and Germany announced it would ban the chemical by 2023. Several other countries have put in place partial or sub-national bans or restrictions on the use of glyphosate, although in many cases these restrictions apply to private use and there are exceptions for agriculture. The growing list of jurisdictions around the world that are putting restrictions in place, whether national or sub-national, shows the extent to which the ground is shifting with respect to the regulatory context.

As these regulatory decisions unfolded, the global supply of glyphosate also became more constrained, after China began to pursue more aggressive inspections at chemical manufacturing facilities following the adoption of a new environmental protection law earlier that year. A number of chemical firms that produced glyphosate for export were shut down by the Chinese government for pollution infractions, and the result was a weaker global supply of glyphosate, and upward price pressure on the chemical (Pratt 2019). It is not clear whether higher prices for the chemical affected the decisions of other governments to restrict its use.

As these regulatory and market dynamics unfolded, the agricultural input firms increased their investment in technological innovations that would at least partially address the growing concerns about the chemical even while continuing to rely on it. Glyphosate resistant weeds had by this time become a major problem in the sector that the firms could not deny or ignore (Bonny 2016). The agricultural input firms began to introduce genetically engineered crops that are resistant to the application of multiple types of herbicides, including both glyphosate and the older, more toxic herbicide dicamba, as a way to provide farmers with more options for weed management, although increased spraying of dicamba has introduced further concerns about exposure to toxic chemicals. They also began to invest in 'digital' agricultural technologies that rely on big data and artificial intelligence analytics to enable farmers to manage chemical use more precisely on their farms (Rotz et al. 2019). Precision spraying equipment, for example, can enable farmers to reduce chemical spraying to only the minimum amount required.

[1] For a complete and updated list of jurisdictions with restrictions on glyphosate, see: https://www.baumhedlundlaw.com/toxic-tort-law/monsanto-roundup-lawsuit/where-is-glyphosate-banned/

The input firms also embraced genome editing technology, in order to develop new seeds using new gene editing techniques that were much cheaper, and much faster, than more 'traditional' agricultural biotechnology (Lassoued et al. 2019) to make precise edits to turn on or off certain traits (Bartowski et al. 2018). Despite claims from the firms that gene editing opens the potential to bring a wide range of useful traits to crops, in practice those same firms sought to develop seeds similar to those they developed with agricultural biotechnology, specifically to make crops tolerant to herbicides, including glyphosate (Dickson et al. 2019).

This strategy of keeping glyphosate in a central role in agricultural systems sits in stark contrast to growing concerns about its use and the expanding economic liability that the large agricultural input firms face from its continued use. A growing number of court cases were filed against Monsanto (and subsequently against Bayer, which bought Monsanto in 2018, discussed more fully in Section IV), claiming that the firm was negligent in warning users about its potential harms. While the firm was confident it would be vindicated in the legal proceedings, given that the regulatory bodies in the US, EU, and Canada had deemed the chemical safe, it lost the first three of these court cases and was ordered to pay out millions in compensation, and the firm is appealing the rulings. By 2020, Bayer, facing over 100,000 lawsuits, settled with the plaintiffs for over US$10 billion (Miller 2020).

IV. Constraints on Weed Control Innovation: The Role of Corporate Market Power

While the three configurations of technology-market-regulatory forces outlined above worked to expand and increase glyphosate's use in a more direct sense, a fourth configuration of forces worked more broadly to constrain innovation in alternative modes of weed control and as such reinforced lock-in of glyphosate-based technologies. Specifically, growing corporate concentration and market power in the agricultural input industry combined with a retreat of the state from its prior role in supporting agricultural research and innovation led to growing corporate influence over the direction of agricultural R&D. This shift in the locus of agricultural research from the public to the private sector is important, as it shapes innovation choices and can favor certain technologies over others (Vanloqueren and Baret 2009). These dynamics, which have intensified in recent decades, have resulted in a narrowing of the agricultural innovation agenda, dampening research into new, safer chemical herbicides as well as non-chemical modes of weed control.

The agrochemical industry has seen nearly continual consolidation, with firms merging and acquiring one another on a regular basis over the past 50 years. According to Bryant et al. (2016, p.7) there were over 70 pesticide manufacturers in the US in the 1960s. Consolidation began in the late 1960s, as declining profits linked to more stringent safety and environmental regulations at that time prompted match-ups among agrochemical firms (Fernandez-Cornejo and Just 2007). As firms in the sector began to merge, agrochemical R&D became concentrated in fewer firms. For example, between 1972 and 1989, the number of pesticide firms with US R&D operations dropped from 33 to 19 (Ollinger and Fernandez-Cornejo 1998, p.141).

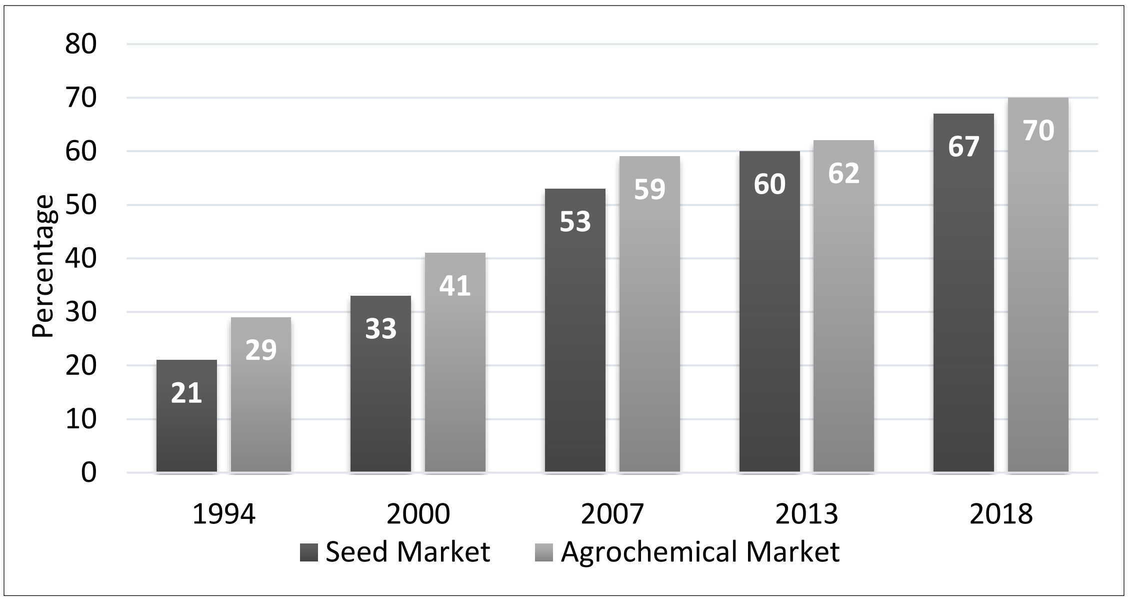
In this period, private sector R&D in crop seeds, a domain previously dominated by the public sector, began to increase rapidly with the bulk of that new research in seed trait agricultural biotechnology, as outlined in Section III, rather than into developing new pesticides and herbicides (Fuglie et al. 2018). As Fuglie and Toole (2014, p.864) note, "…by the late 1990s, private crop seed/biotechnology research had surpassed research in all other agricultural input sectors." As private sector R&D shifted from agrochemicals to agricultural biotechnology from the 1980s onward, public sector agricultural R&D more broadly began to level off (Fuglie et al. 2018).

The 1990s and early 2000s saw additional mergers in the agricultural input sector that further intensified these trends, in particular the merger of chemical and seed companies, to carry out the agricultural biotechnology strategy. Dupont, a chemical company, acquired the largest seed company at the time, Pioneer Hi-Bred, in 1999. Pioneer had itself acquired a number of smaller seed companies throughout the 1970s and 1980s, in previous merger clusters. In 2000, AstraZeneca and Novartis, both specializing in pharmaceuticals and chemicals, merged and spun off their own agricultural chemical arm to form Syngenta. Monsanto, originally a chemical company, also purchased a number of seed and biotech companies in the 1990s and merged with pharmaceutical firm Pharmacia & Upjohn in 2000, from which its agricultural input business was spun off as Monsanto in 2002. Dow Chemical purchased Mycogen, a seed and biotech firm, in the mid-1990s, and also purchased various seed, chemical and biotech firms after 2000 to form Dow AgroSciences. In 2002, Bayer acquired Aventis, which itself was the product of a merger of chemical firms AgrEvo and Rhone Poulenc in 1999 (Howard 2009).

Extensive mergers of the 1990s and first decade of the 2000s resulted in the reduction of a significant segment of the agrochemical market by to just six massive firms – commonly referred to as "the Big Six" – that controlled around 75% of the market by 2013 (ETC Group, 2015, p.5). At this same time, five of the top seven firms producing herbicides were also major agricultural biotechnology seed companies (i.e. Syngenta, Monsanto, Dupont, Dow, Aventis). By 2006, just five agrochemical companies conducted 74% of R&D into crop protection (pesticides and herbicides) (Fuglie et al. 2011, p.16).

The consolidation in the sector continued (Clapp 2018). In late 2015, agrochemical giants Dow and DuPont announced that they would merge, which set off a series of other deals that eventually saw the Chinese agrochemical firm, ChemChina, purchase Syngenta, and the German agrochemical firm, Bayer, purchase Monsanto. BASF, also a major agrochemical firm, purchased the parts of these firms that regulators required them to sell to get the mergers approved. The result was that just four firms came to dominate the agricultural input industry (Bonny 2017). The impetus for the most recent mergers was a series of factors. One was weak profits in the sector as commodity prices fell after 2014, which prompted countries in South America, the largest market for agrochemicals, to reduce their purchases of inputs. Another was a desire to move into digital farming and genome editing technologies, outlined above (OECD 2018; Clapp and Ruder 2020).

Figure 5. Market Share of the Top 4 Firms in Global Seeds and Agrochemicals, 2000-2018



Sources: Compiled from data in Fuglie et al. 2011; ETC Group data: www.etcgroup.org

As this consolidation took place in the agrochemical and seed industry, the market share of the top four firms steadily climbed, as Figure 5 illustrates. Growing market share of a large few firms at the top signals the growing market power of these firms. Market power is typically considered to be significant in a sector when the top four firms have over 40% or more of the market share. In the agricultural input industry, this threshold was easily reached in the early to mid-2000s. High levels of market power are problematic for several reasons. Economists warn that it can lead to higher prices for products because there is naturally less competition with fewer players in the market (Díez et al. 2018). Although intellectual property rights such as patents can enable firms to charge higher prices during the period of patent protection, there are still concerns that market concentration could drive prices higher than warranted even in cases where IPRs are present (Fuglie et al. 2018).

Elevated levels of market power can also dampen innovation, which in turn can affect consumer choice and overall scientific advancement. A recent IMF study suggests that the market power of corporate giants, especially those firms that operate in highly concentrated markets, can lead to weaker levels of investment and innovation (Díez et al. 2018, p.12-14). The authors of that study found that while the higher profits that accrue to these firms can initially be invested by firms to spur further technological innovation, the relationship turns more strongly negative in industries that have very high levels of concentration (Díez et al. 2018, 12-14). In the agricultural biotechnology sector, Schimmelfennig et al. (2004) found that after initial innovations that occurred after firms began to merge in the 1980s and 1990s, the intensity of R&D declined. Other economists who have examined this question in the agricultural biotechnology sector have found mixed results in terms of spending (Fuglie et al. 2018). However, as Fuglie and colleagues note, concentration in the sector and high fixed R&D costs can stifle innovation in other ways, because high R&D costs present significant barriers to entry for smaller and more innovative firms. The result is a reduction in the number and types of innovations, thus leaving farmers with less choice (Fuglie et al. 2018).

Looking specifically at weed control innovation, the data show that R&D has not delivered much new in the era of heightened corporate consolidation. In the 1960s and 1970s, new active ingredients for herbicides were typically introduced every one or two years, in a bid to create new markets as patents expired on previous chemicals (Dayan 2019). However, after corporate consolidation trends intensified after the late 1980s and early 1990s, R&D into new active ingredients for herbicides dwindled. Research and development spending in the crop protection sector fell in real terms from 1994 to 2010 (Fuglie et al. 2011, p.49). The number of registered patents for herbicides declined from around 180 in 1995 to just 50 in 2002 (Rüegg et al. 2006, p.272). As Duke points out, only around 20 modes of action for weed control are currently used in agriculture today, all of which were discovered many years ago when many more firms were in the business (Duke 2011). Monsanto, for example, ceased to conduct R&D into crop protection chemicals altogether after the expiry of its glyphosate patent in 2000 (Fuglie et al. 2011).

Herbicide scientists have expressed concern that no new modes of action for crop protection chemicals have been introduced in over 30 years (Appleby 2005; Duke 2012; Dayan 2019). Duke (2012) notes, for example, that corporate consolidation has reduced the number of scientists working on these problems, which has led to lower diversity in research groups and weakened innovation. Indeed, following the announcements of the most recent mega-mergers, the firms involved clearly stated that they were planning to make cutbacks to R&D budgets, rather than increasing them. Just prior to their merger, Dow and DuPont, for example, referred to these cuts, which resulted in the loss of thousands of jobs, as “global optimization of R&D” in their agriculture divisions (e.g. Dow and Dupont 2016, p.22).

The result of this weakening of R&D spending is that firms are much more likely to focus narrowly on technologies that have already been developed or explore only those innovations that deliver the highest commercial payoffs, such as genetically modified seeds that work with existing, already approved chemicals such as glyphosate. As the problem of glyphosate resistant weeds has grown, for example, firms such as Monsanto (now merged with Bayer) are engineering plants that are tolerant to additional herbicides beyond glyphosate, to give farmers more choice in the chemicals they spray to better manage herbicide-resistant weeds. One of these additional herbicides is dicamba. Because dicamba is highly toxic and prone to drift when sprayed, it can pose threats to crops that are not tolerant to it. Some analysts are also concerned that weeds will also develop resistance to dicamba, repeating the same cycle as occurred with glyphosate (Vieira et al. 2020).

The leading agrochemical firm, Bayer, has recognized that there are few alternative herbicide options. In mid-2019, as the law suits were stacking up against it, the firm announced that it planned to dedicate US$5.5 billion to research alternative weed control technologies, even as it stressed in the same announcement that "Glyphosate will continue to play an important role in our portfolio" (Bayer 2018). In early 2020 Bayer indicated that it had discovered a new molecule that could be the basis for a new chemical herbicide. Other agrochemical firms, including FMC Corp and BASF are also working toward developing new chemical herbicides (Bunge 2020). It remains to be seen whether these new herbicides, once developed, are less toxic than older chemicals. It is also clear that the aim of this research is to substitute one chemical herbicide for another, rather than to redesign agricultural systems away from the use of chemical herbicides.

Indeed, there has been a severe shortage of funding and support for approaches to weed control that carry less risk for the environment and for human health. Research funding in support of innovations in organic and agroecological farming methods that rely on non-chemical techniques, such as crop rotations, mulching, and mechanical and thermal methods of weed control, has been far outpaced by research supporting chemical dependent agriculture (Vanloqueren and Baret 2009). Recent studies analyzing the allocation of publicly funded agricultural research in the US, for example, have found that although a significant amount of projects do income at least some component of sustainability, those projects tend to focus on improving efficiency of input use or substituting inputs, rather than system redesign based on agroecological principles (DeLonge et al. 2016; Miles et al. 2017). Similar patterns exist elsewhere, including international assistance for agroecology projects (Pimbert and Moeller 2018).

In addition to shaping the innovation agenda, concentrated levels of market power also enhance the political power of firms – as they are able to lobby in a more coordinated way to influence policy and regulation in ways that strengthen their own bottom line (Khan and Vaheesan 2017, 266). With respect to the agricultural input industry, Fernandez-Cornejo and Just (2007, p.1269) call this concentrated lobby power in the sector a kind of "political economy of scale in influencing government regulations." Indeed, as already outlined, these firms actively worked to influence the regulatory context for agricultural biotechnology and herbicides that shaped their ability to amass even more market power (Newell 2006; Glover 2010; Khan 2013). In this way, the configurations that led to greater glyphosate use – both explicitly and through constraints on innovation into alternatives – are closely intertwined with the tendency toward corporate consolidation.

Conclusion

The analysis in this paper outlines how distinct yet overlapping configurations of technology, market, and regulatory forces have effectively locked-in glyphosate as a central input in modern industrial agriculture. The nature of the interplay of these forces was somewhat different in each of these configurations. The repurposing of glyphosate in the 1980s and 1990s emerged from rising costs for herbicide development due to increased regulations compared with seed development to work with existing herbicides that were made possible by other regulatory decisions that allowed IPR protection on genetically altered seeds. The rise of the generic market emerged in response to the expired patent on glyphosate combined with rising demand for the product from key developing countries that had given approval to GM crops, while widely available inexpensive glyphosate encouraged wider technological practices that relied on the chemical such as crop desiccation and no-till agriculture. The central role of glyphosate in new digital and genome editing technologies emerged as its use became increasingly contested due to health and environmental concerns and as a growing number of states are considering regulatory control. At the same time, a broader configuration of increased market concentration and power of the large agricultural input firms in the context of gradual government reduction of its role in agricultural R&D worked to constrain innovation into alternative solutions to weed control. Both aspects of technological lock-in – encouragement of its use, and discouragement of innovation in alternatives – are important in understanding the nature and extent of the centrality of glyphosate, and increasingly other toxic herbicides such as dicamba, in agricultural systems.

This analysis adds nuance to the existing literature in several ways. While it affirms that the rise of agricultural biotechnology is indeed an important element of the expansion of glyphosate as a key agricultural input, it also shows that a fuller account requires a broader consideration of how technological change and its adoption is entwined in a complex interplay with changing market conditions and developments in the regulatory and policy environment. This insight contributes to a broader understanding of the dynamics surrounding technological lock-ins, by showing that multiple configurations of dynamics between markets, technology, and state regulation can exist at the same time, reinforcing one another in ways that are important to understand if the aim is to unwind locked-in technologies in a bid to move toward more sustainable practices. This study also provides lessons for broader conceptual frameworks for IPE and IPEE. While Strange (1996) focused primarily on the ways in which technological change could influence the balance of power in state-market relationships, this research shows that technology, markets and state policies interact in complex, multidirectional and layered ways that can shape not just the distribution of power in the global economy, but also environmental consequences associated with it. The findings regarding glyphosate's entrenchment also supplement earlier work on the political economy of biotechnology that revealed how technological development contributed to the growing power of the agribusiness corporations. The glyphosate case adds nuance to these findings by showing how regulation, technology, and market dynamics not only contribute to a concentration of power among agribusiness firms, but also how corporate power further shapes technological innovation in the sector, which has important implications for both the environment and public health.

It is as yet unclear whether the cycle of technology-market-state configurations reinforcing greater glyphosate use will be broken any time soon. Growing contestation over the environmental and health implications of the herbicide is clearly affecting government regulatory decisions, which will play a prominent role in determining whether the pursuit of technological innovations that revolve around glyphosate will remain profitable for the agricultural input firms. At the same time, if states wish to move beyond the herbicide centric model of agriculture, it is vital that, in addition to passing legislation regarding registrations of specific herbicides, that they implement measures that address the overlapping configurations encouraging its use, as well as the forces discouraging research and innovation into alternative. This includes, for example, investing in public sector research into agroecology and other agricultural models that do not rely on herbicides.

References

Appleby, Arnold P. 2005. A History of Weed Control in the United States and Canada – A Sequel. *Weed Science* 53 (6): 762–68.

Arthur, W. Brian. 1989. Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal* 99 (394): 116–131.

Bain, Carmen, Theresa Selfa, Tamera Dandachi, and Sara Velardi. 2017. 'Superweeds' or 'Survivors'? Framing the Problem of Glyphosate Resistant Weeds and Genetically Engineered Crops. *Journal of Rural Studies* 51: 211–21.

Bartkowski, Bartosz, Insa Theesfeld, Frauke Pirscher, and Johannes Timaeus. 2018. Snipping around for Food: Economic, Ethical and Policy Implications of CRISPR/Cas Genome Editing. *Geoforum* 96: 172–80.

Bayer. 2018. Global Leaders Reiterate Importance of Glyphosate. Available online at: https://www.bayer.com/en/bayer-global-glyphosate-leaders-comments.pdfx?forced%3Dtrue, last accessed April 12, 2020.

Bayer. 2019. We Listened. We Learned. June 14. Available online at: https://www.bayer.com/en/our-commitments-on-transparency-sustainability-and-engagement.aspx, last accessed April 12, 2020.

Benbrook, Charles M. 2016. Trends in Glyphosate Herbicide Use in the United States and Globally. *Environmental Sciences Europe* 28 (3).

Benbrook, Charles M. 2019. How Did the US EPA and IARC Reach Diametrically Opposed Conclusions on the Genotoxicity of Glyphosate-Based Herbicides? *Environmental Sciences Europe* 31: 2.

Bonny, Sylvie. 2016. Genetically Modified Herbicide-Tolerant Crops, Weeds, and Herbicides: Overview and Impact. *Environmental Management* 57 (1): 31–48.

Bonny, Sylvie. 2017. Corporate Concentration and Technological Change in the Global Seed Industry. *Sustainability* 9(9): 1632.

Bryant, Henry, Aleksandre Maisashvili, Joe Outlaw, and James Richardson. 2016. *Effects of Proposed Mergers and Acquisitions Among Biotechnology Firms on Seed Prices*. Agricultural and Food Policy Center, and Texas A&M University. Available Online at: https://www.afpc.tamu.edu/pubs/0/675/WP_16-2.pdf, last accessed March 5, 2020.

Bunge, Jacob. 2020. Bayer Touts Herbicide Research Discovery. *Wall Street Journal*. February 14.

Canadian Food Inspection Agency (CFIA). 2017. Safeguarding with Science: Glyphosate Testing in 2015-2016. *CFIA-Science Branch Survey Report, Food Safety Science Directorate.* Available online at: http://static.producer.com/wp-content/uploads/2017/04/CFIipesA_ACIA-9123346-v1-FSSD-FSSS-Glyphosate-Final-Report-15-16_0184101.pdf#_ga=1.196489061.892407858.1492107204, last accessed March 5, 2020.

China National Chemical Information Center (CNCIC). 2009. Analysis of Development of Pesticide Formulations and Prospects of Various Glyphosate Formulations (translated from Chinese). Available online at: http://chem.ckcest.cn/article/details/804b3dd8-e5fa-4825-9693-12b51b8f94fa, last accessed April 12, 2020.

Clapp, J. 2018. Mega-Mergers on the Menu: Corporate Concentration and the Politics of Sustainability in the Global Food System. *Global Environmental Politics* 18 (2): 12-33

Clapp, J. 2003. Transnational Corporate Interests and Global Environmental Governance: Negotiating Rules for Agricultural Biotechnology and Chemicals. *Environmental Politics* 12 (4): 1-23.

Clapp, J. and E. Helleiner. 2012. International Political Economy and the Environment: Back to the Basics? *International Affairs*, 88 (3): 485-501.

Cuhra, Marek, Thomas Bøhn, and Petr Cuhra. 2016. Glyphosate: Too Much of a Good Thing? *Frontiers in Environmental Science* 4 (28): 1-14.

Davis, Adam S., and George B. Frisvold. 2017. Are Herbicides a Once in a Century Method of Weed Control? *Pest Management Science* 73 (11): 2209–20.

Dayan, Franck E. 2019. Current Status and Future Prospects in Herbicide Discovery. *Plants* 8 (9): 341.

DeLonge, Marcia, Albie Miles, and Liz Carlisle. 2016. Investing in the Transition to Sustainable Agriculture. *Environmental Science & Policy* 55: 266–73.

Dickson, Duane, Shay Eliaz and Aijaz Hussain. 2019. The Future of Agrochemicals: Capturing Value through Innovation, Resourcefulness and Digital Alchemy. *Deloitte*. Available Online at: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-eri-future-of-agrochemicals.pdf, last accessed March 5, 2020.

Diez, F., Leigh, D., and S. Tambunlertchai. 2018. Global Market Power and its Macroeconomic Implications. *IMF Working Paper WP/18/137*. Washington, D.C.: IMF.

Dow and DuPont. 2016. Merger of Equals Update. Available Online at: https://s2.q4cdn.com/752917794/files/doc_presentations/2016/presentation/DWDP-Investor-Deck-Final.pdf, last accessed March 5, 2020.

Duan, Y. 2014. Environmental Audit of Glyphosate Opening a New Era of China's Pesticide Industry. China Crop Protection Industry Association (translated from Chinese). Available online at: http://www.ccpia.org.cn/u/cms/www/201703/311648556pga.pdf, last accessed April 12, 2020.

Duke, Stephen O., and Stephen B. Powles. 2008. Glyphosate: A Once-in-a-Century Herbicide. *Pest Management Science* 64 (4): 319–25.

Duke, Stephen O. 2012. Why Have No New Herbicide Modes of Action Appeared in Recent Years? *Pest Management Science* 68 (4): 505–12.

Dupraz, Emily. 2012. Monsanto and the Quasi-Per Se Illegal Rule for Bundled Discounts. *Vermont Law Review* 37: 203–37.

ETC Group. 2015. *Breaking bad: Big Ag Mega-Mergers in Play* Communique #115. Available online at: http://www.etcgroup.org/sites/www.etcgroup.org/files/files/etc_breakbad_23dec15.pdf, last accessed April 12, 2020.

Fernandez-Cornejo, Jorge, and Richard E. Just. 2007. Researchability of Modern Agricultural Input Markets and Growing Concentration. *American Journal of Agricultural Economics* 89 (5): 1269-1275.

Fernandez-Cornejo, Jorge. 2004. *The Seed Industry in U.S. Agriculture: An Exploration of Data and Information on Crop Seed Markets, Regulation, Industry Structure, and Research and Development.* Washington, D.C.: USDA. Available Online at: http://ageconsearch.umn.edu/handle/33671, last accessed March 5, 2020.

Fuglie, Keith, Paul Heisey, John King, Carl Pray, Kelly Day-Rubenstein, David Schimmelpfennig, Sun Ling Wang, and Rupa Karmarkar-Deshmukh. 2011. Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries Worldwide. *United States Department of Agriculture, Economic Research Service*. Available Online at: https://www.ers.usda.gov/webdocs/publications/err130/11777_err130_1_.pdf, last accessed March 5, 2020.

Fuglie, Keith O., and Andrew A. Toole. 2014. The Evolving Institutional Structure of Public and Private Agricultural Research. *American Journal of Agricultural Economics* 96 (3): 862–83.

Fuglie, Keith. 2016. The Growing Role of the Private Sector in Agricultural Research and Development World-Wide. *Global Food Security* 10: 29–38.

Fuglie, Keith O., Matthew Clancy, and Paul W. Heisey. 2018. Private-Sector Research and Development. In Nicholas Kalaitzandonakes, Elias G. Carayannis, Evangelos Grigoroudis, and Stelios Rozakis (eds). *From Agriscience to Agribusiness: Theories, Policies and Practices in*

Technology Transfer and Commercialization, p.41–73. Innovation, Technology, and Knowledge Management Series. Cham, Switzerland: Springer International Publishing.

Gillam, Carey. 2017. *Whitewash: The Story of a Weed Killer, Cancer, and the Corruption of Science*. Washington, D.C.: Island Press.

Gillam, Carey. 2019. Monsanto Exec Reveals $17 Million Budget for Anti-IARC, Pro-Glyphosate Efforts. *US Right To Know.* Available Online at: https://usrtk.org/monsanto-roundup-trial-tacker/monsanto-executive-reveals-17-million-for-anti-iarc-pro-glyphosate-efforts, last accessed March 5, 2020.

Glover, Dominic. 2010. The Corporate Shaping of GM Crops as a Technology for the Poor. *Journal of Peasant Studies* 37 (1): 67–90.

Heap, Ian. 2020. International Herbicide-Resistant Weed Database. Available Online at: http://www.weedscience.org/default.aspx, last accessed March 5, 2020.

Hébert, Marie-Pier, Vincent Fugère, and Andrew Gonzalez. 2019. The Overlooked Impact of Rising Glyphosate Use on Phosphorus Loading in Agricultural Watersheds. *Frontiers in Ecology and the Environment* 17 (1): 48–56.

Howard, Philip. 2009. Visualizing consolidation in the global seed industry: 1996–2008. *Sustainability*, *1*(4): 1266-1287.

Howard, Philip. 2015. Intellectual Property and Consolidation in the Seed Industry. *Crop Science* 55(6): 2489.

International Agency for Research on Cancer (IARC). 2018. *IARC response to criticisms of the Monographs and the glyphosate evaluation*. Available Online at: https://www.iarc.fr/wp-content/uploads/2018/07/IARC_response_to_criticisms_of_the_Monographs_and_the_glyphosate_evaluation.pdf, last accessed March 5, 2020.

International Service for the Acquisition of Agri-biotech Applications (ISAAA). 2018. Global Status of Commercialized Biotech/GM Crops in 2018. Brief No 54. Ithaca, NY: ISAAA.

International Service for the Acquisition of Agri-biotech Applications (ISAAA). 2017. Global Status of Commercialized Biotech/GM Crops in 2017. Brief No 53. Ithaca, NY: ISAAA.

Kassam, A., T. Friedrich, and R. Derpsch. 2019. Global Spread of Conservation Agriculture. *International Journal of Environmental Studies* 76 (1): 29–51.

Khan, Lina. 2013. How Monsanto Outfoxed the Obama Administration. *Salon.* March 15.

Khan, Lina, and Vaheesan, Sandeep. 2017. Market Power and Inequality: The Antitrust Counterrevolution and Its Discontents. *Harvard Law & Policy Review* 11: 235-294.

Krimsky, Sheldon, and Carey Gillam. 2018. Roundup Litigation Discovery Documents: Implications for Public Health and Journal Ethics. *Journal of Public Health Policy* 39 (3): 318–26.

Levy, David and Peter Newell (eds). 2005. *The Business of Global Environmental Governance*. Cambridge, MA: MIT Press.

Miles, Albie, Marcia DeLonge, and Liz Carlisle. 2017. Triggering a Positive Research and Policy Feedback Cycle to Support a Transition to Agroecology and Sustainable Food Systems. *Agroecology and Sustainable Food Systems* 41 (7): 855–79.

Miller, Joe. 2020. Bayer to Pay up to $10.9bn to Settle US Roundup Lawsuits. *Financial Times.* June 24.

Monsanto. 2017. IARC's Report on Glyphosate. April 21. Available online at: https://monsanto.com/company/media/statements/glyphosate-report-response/, last accessed March 5, 2020.

Myers, John Peterson, Michael N. Antoniou, Bruce Blumberg, Lynn Carroll, Theo Colborn, Lorne G. Everett, Michael Hansen, et al. 2016. Concerns over Use of Glyphosate-Based Herbicides and Risks Associated with Exposures: A Consensus Statement. *Environmental Health* 15 (19): 1-13.

Nehring, Richard. 2019. Pest Management. In Hellerstein, Daniel, Dennis Vilorio and Marc Ribado (eds) *Agricultural Resources and Environmental Indicators, 2019*. Washington, D.C.: US Department of Agriculture.

Nelson, Arthur. 2019. EU Glyphosate Approval was based on Plagiarised Monsanto Text, Finds. *The Guardian.* 16 January.

Newell, Peter. 2006. Corporate Power and 'Bounded Autonomy' in the Global Politics of Biotechnology. In R. Falkner (ed) *The International Politics of Genetically Modified Food* (pp. 67-84). Palgrave Macmillan, London.

Newell, Peter and Mackenzie, Ruth. 2004 Whose Rules Rule? Development and the Global Governance of Biotechnology. *IDS Bulletin* 35(1): 82–91.

Noori, Jafar, Maria Dimaki, John Mortensen, and Winnie Svendsen. 2018. Detection of Glyphosate in Drinking Water: A Fast and Direct Detection Method without Sample Pretreatment. *Sensors* 18 (9): 2961.

Ollinger, Michael, and Jorge Fernandez-Cornejo. 1998. Sunk Costs and Regulation in the U.S. Pesticide Industry. *International Journal of Industrial Organization* 16 (2): 139–68.

Ollinger, Michael, and Jorge Fernandez-Cornejo. 1995. *Regulation, Innovation, and Market Structure in the U.S. Pesticide Industry.* USDA Economic Research Service. Agricultural Economic Report No. 719.

Ollinger, Michael, and Leslie Pope. 1995. Strategic Research Interests, Organizational Behavior, and the Emerging Market for the Products of Plant Biotechnology. *Technological Forecasting and Social Change*, Biotechnology and the Future of Agriculture and Natural Resources, 50 (1): 55–68.

Organisation for Economic Cooperation and Development (OECD). 2018. *Concentration in Seed Markets: Potential Effects and Policy Responses*. Paris: OECD. Available online at: https://doi.org/10.1787/9789264308367-en, last accessed January 26, 2021.

Osteen, Craig D, and Jorge Fernandez-Cornejo. 2016. Herbicide Use Trends: A Backgrounder. *Choices* 31 (4). Agricultural and Applied Economics Association.

Phillips McDougall. 2016. *The Cost of New Agrochemical Product Discovery, Development and Registration in 1995, 2000, 2005-8 and 2010-2014*. Available Online at: http://www.seedquest.com/News/pdf/2016/PMcD.pdf, last accessed March 5, 2020.

Phillips McDougall. 2018. *Evolution of the Crop Protection Industry since 1960*. Available online at: https://croplife.org/the-changing-face-of-the-pesticide-industry/, last accessed April 12, 2020.

Pimbert, Michel, and Nina Isabella Moeller. 2018. "Absent Agroecology Aid: On UK Agricultural Development Assistance Since 2010." *Sustainability* 10 (2): 505.

Pratt, Sean. 2019. Chinese Crackdown Threatens Pesticide Supply. *Western Producer*, May 9.

Rotz, Sarah, Emily Duncan, Matthew Small, Janos Botschner, Rozita Dara, Ian Mosby, Mark Reed, and Evan D. G. Fraser. 2019. The Politics of Digital Agricultural Technologies: A Preliminary Review. *Sociologia Ruralis* 59 (2): 203-229.

Rüegg, W T, M Quadranti, and A Zoschke. 2007. Herbicide Research and Development: Challenges and Opportunities. *Weed Research* 47 (4): 271–75.

Schimmelpfennig, David E., Carl E. Pray, and Margaret F. Brennan. 2004. The Impact of Seed Industry Concentration on Innovation: A Study of US Biotech Market Leaders. *Agricultural Economics* 30 (2): 157–67.

Schneider, Keith. 1990. Betting the Farm on Biotech. *New York Times*. June 10.

Schütte, Gesine, Michael Eckerstorfer, Valentina Rastelli, Wolfram Reichenbecher, Sara Restrepo-Vassalli, Marja Ruohonen-Lehto, Anne-Gabrielle Wuest Saucy, and Martha Mertens.

2017. Herbicide Resistance and Biodiversity: Agronomic and Environmental Aspects of Genetically Modified Herbicide-Resistant Plants. *Environmental Sciences Europe* 29 (1): 5.

Sell, Susan K. 2009. Corporations, seeds, and intellectual property rights governance. In Clapp, Jennifer and Doris Fuchs (eds). *Corporate Power in Global Agrifood Governance*, p.187-223. Cambridge, MA: MIT Press.

Seto, Karen, Steven Davis, Ronald Mitchell, Eleanor Stokes, Gregory Unruh, and Diana Ürge-Vorsatz. 2016. Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources* 41: 425–52.

Solomon, Keith R. 2019. Estimated Exposure to Glyphosate in Humans via Environmental, Occupational, and Dietary Pathways: An Updated Review of the Scientific Literature. *Pest Management Science*.

Swinton, Scott and Braeden Van Deynze. Hoes to Herbicides: Economics of Evolving Weed Management in the United States. *European Journal of Development Research* 29(3): 560–74.

Timmons, F. L. 2005. A History of Weed Control in the United States and Canada. *Weed Science* 53 (6): 748–61.

Torretta, Vincenzo, Ioannis A. Katsoyiannis, Paolo Viotti, and Elena Cristina Rada. 2018. Critical Review of the Effects of Glyphosate Exposure to the Environment and Humans through the Food Supply Chain. *Sustainability* 10 (4): 950.

Tosun, Jale, Herman Lelieveldt, and Trevelyan S. Wing. 2019. A Case of 'Muddling Through'? The Politics of Renewing Glyphosate Authorization in the European Union. *Sustainability* 11 (2): 440.

Strange, Susan. 1996. *The Retreat of the State: The Diffusion of Power in the World Economy*. Cambridge: Cambridge University press.

Székács, András, and Béla Darvas. 2018. Re-Registration Challenges of Glyphosate in the European Union. *Frontiers in Environmental Science* 6 (78): 1-36.

US Environmental Protection Agency (EPA). Registration of Pesticides in the United States: Proposed Guidelines; Economic Impact Analysis. Office of the Federal Register, National Archives and Records Administration. 1978. *Federal Register* 43 (173): 39644-656.

Vanloqueren, Gaëtan, and Philippe V. Baret. 2009. How Agricultural Research Systems Shape a Technological Regime That Develops Genetic Engineering but Locks out Agroecological Innovations. *Research Policy* 38 (6): 971–983.

Vieira, Bruno, Joe D. Luck, Keenan L. Amundsen, Rodrigo Werle, Todd A. Gaines, and Greg R. Kruger. 2020. Herbicide Drift Exposure Leads to Reduced Herbicide Sensitivity in Amaranthus Spp. *Scientific Reports* 10 (1): 2146.

Wield, David, Joanna Chataway, and Maurice Bolo. 2010. Issues in the Political Economy of Agricultural Biotechnology. *Journal of Agrarian Change* 10 (3): 342–366.

Williams, Marc. 2009. Feeding the World? Transnational Corporations and the Promotion of Genetically Modified Food." In *Corporate Power in Global Agrifood Governance*. In Clapp, Jennifer and Doris Fuchs (eds). *Corporate Power in Global Agrifood Governance*, p.187-223. Cambridge, MA: MIT Press, 155-186.

World Health Organization (WHO). 2015. *IARC Monographs Volume 112: Evaluation of Five Organophosphate Insecticides and Herbicides*. International Agency for Research on Cancer.

Xu, Jingwen, Shayna Smith, Gordon Smith, Weiqun Wang, and Yonghui Li. 2019. Glyphosate Contamination in Grains and Foods: An Overview. *Food Control* 106: 106710.