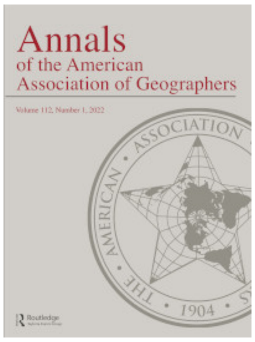

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The Glyphosate Assemblage: Herbicides, Uneven Development, and Chemical Geographies of Ubiquity

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The ubiquity of chemicals demands new ways of thinking about human–nature assemblages. This article develops a dialogue between agrarian political economy, critical commodity chains research, and chemical geographies through a case study of the world's most widely used agrochemical: glyphosate, commonly known as Monsanto's Roundup. In the 1980s, glyphosate triumphed as a benign biocide that promised both safety and effectiveness. This construct made possible a capitalist agricultural assemblage characterized by chemical pervasiveness, first as a chemical replacement for mechanical tillage and since the 1990s as the chemical input for genetically modified seed packages. The ubiquity that characterizes the glyphosate assemblage is also a geography of uneven development comprising shifting firm networks, policies, and trade. Central to this assemblage since 2000, yet largely ignored, is the outsized expansion of second- and third-tier generic pesticide producers, especially in China, for whom glyphosate is part of a network entry and upgrading development strategy. Today, the glyphosate assemblage faces unprecedented challenges from weed resistance and health controversies. Whether and how the herbicide assemblage restabilizes will be determined by the complex environmental *and* developmental challenges of chemical agriculture and pervasive chemicals broadly, which highlights the need for a transdisciplinary dialogue that cuts across these domains. *Key Words: assemblages, generic herbicides, health, south–south production networks, weed resistance.*

> [As a result of our struggle] we got just a 2,500-meter buffer. Today, they don't spray there but 33 percent of the population already has cancer and 80 percent of the children have agrochemicals in their bloodstream … endosulfan, DDT, 2,4-D, glyphosate. My daughters have all those agrochemicals, not just one poison but a cocktail of poisons.
>
> —Sofía Gatica, Madres de Ituzaingó (interview 9 April 2018)

> The plant physiologist (Dr. Douglas Baird) who evaluated the field trials in September 1970 was so impressed by the results that his report to management was captioned "EUREKA."
>
> —Franz, Mao, and Sikorski (1997, 7)

Glyphosate has been labeled a "once-in-a century herbicide" (Duke and Powles 2008). Launched in 1972 and commercialized in 1976 by Monsanto under the trade name Roundup, the compound represented a seemingly ideal combination of effectiveness and safety. Glyphosate was the most efficient plant killer synthesized to date, eliminating more plants designated as weeds than any other herbicide discovered by modern weed science (Zimdahl 2010). It acted systemically: Translocated from leaf surfaces throughout the plant, it blocked a key amino acid synthesis pathway (the shikimate pathway) leading to plant death after several days. Because the inhibited target enzyme (EPSPS) and associated pathway were unique to plants, Monsanto scientists claimed that the molecule would not harm humans and other nonplant organisms; they also claimed that glyphosate did not bioaccumulate in mammals or persist in soil. These claims stood in sharp contrast to the herbicides widely used at the time, 2,4-D and paraquat, both of which are toxic to humans and animals. Moreover, some scientists argued that plants were unlikely to develop resistance to glyphosate because only a small number of single mutations furnished the trait, did

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so only at low levels, and were not present in wild plants (Heap and Duke 2018). "Eureka" indeed.

Armed with these assurances, glyphosate quickly displaced other competitor compounds and rendered weed specialists' knowledge redundant. The economic impact was staggering. Glyphosate became the largest selling and most profitable herbicide ever marketed (Zimdahl 2010). Global sales increased more than sixteen-fold between 1980 and 2018, accounting for almost 20 percent of the herbicide and more than 8 percent of the entire agrochemical market by 2018. Glyphosate sales that year were nearly six times those of the next highest selling herbicide (glufosinate) and exceeded the largest selling insecticide and fungicide by 3.3 and 3.8 times, respectively (Phillips McDougall [PMD] 2019). As we discuss in what follows, glyphosate—the material compound and the ideational construct of a benign biocide—formed part of—indeed, made possible—a capitalist agricultural assemblage characterized by chemical ubiquity. Our focus on the glyphosate assemblage is motivated in part by the recent public debate over the compound, which has brought this socionatural arrangement into sharp relief as it faces multiple stressors. Glyphosate has made headlines since 2015, when the World Health Organization's (WHO) International Agency for Research on Cancer (2017) upended the already fraught scientific consensus on glyphosate safety and declared it to be a "probable carcinogen." The ruling fueled contentious public and scientific debate along with continuing legal action in numerous jurisdictions over glyphosate's harms (Cuhra, Bøhn, and Cuhra 2016; Myers et al. 2016; Torretta et al. 2018). The promise of future biocide effectiveness has also collapsed: Although glyphosate controls more weeds than any other known herbicide, weeds have in turn developed more strategies to resist glyphosate than they have against any other herbicide (Heap and Duke 2018).

At the heart of both of these challenges to the chemical's twinned promise of safety and effectiveness is glyphosate's very pervasiveness, which in turn poses key challenges to the paradigms of safety and risk that dominate pesticide management. In less than two decades, much of the planet has been covered with glyphosate, in a variety of glyphosate-based herbicide formulations. In many locales, these applications have layered upon already chemical-laden landscapes and bodies, as Sofía Gatica, an activist and community leader fighting pesticide fumigation in Argentina, explained. Glyphosate articulates with already herbicide-resistant plants, creating "symbiotic entanglements" of multiple biocide resistances, so-called superweeds, that have thrown into crisis modern weed science's signal paradigm of chemical control.

The instability of the glyphosate assemblage centers the significance of "chemical geographies" as part of a broader material and epistemological project to bridge dualist nature–society thinking (Barry 2017; Romero et al. 2017). Debates over neoliberal natures and the problematic of the human–planetary interface signaled by various "-cene" concepts (Anthropocene, Plantationocene, etc.) draw attention to the "chemicalization of life" or life understood "as the emergent property of complex flows of chemicals with great temporal and spatial complexity" (Romero et al. 2017, 167; see also Heynen et al. 2007; Bigger et al. 2018). That is, the ubiquity of chemicals combined with newfound anxiety about them demands new ways of thinking about human–nature assemblages and their boundaries. Chemical substances are not external compounds that act on the body; rather, chemical molecules are transformative agents woven through the body–environment, and, as such, have wide-ranging effects on environmental and human health (Guthman and Mansfield 2013; Romero et al. 2017). The prominence of glyphosate makes it central to these new chemical geographies, which we regard as distinct material relations that shape capitalism geopolitically and geoeconomically.

Focusing attention on the glyphosate assemblage itself requires a key shift in the study of pesticides. Much of the critical social science work in this area has been undertaken though a political ecological lens that has focused largely on farmer decision making in the context of global market forces and state promotion of capital intensification (e.g., Thrupp 1990; Grossman 1998; Galt 2014; Shattuck 2019). This research has shown that agrochemical firms and their field agents, as well as pesticide retailers, provide the bulk of technical assistance to farmers, especially after the dismantling of state extension programs under neoliberal structural adjustment (Conroy, Murray, and Rosset 1996; Aga 2018). We augment this research agenda by shifting our analytical focus from pesticides as inputs into agricultural commodity chains toward the pesticide assemblage itself. Our aim is not to ignore the importance of the seed–chemical nexus and related controversies over genetically modified organisms (Kloppenburg [1988] 2004; Schurman and Munro 2013) but to add an additional, and to date underexplored, perspective afforded through the lens of the chemical itself (see also Shattuck forthcoming). As we demonstrate in what follows, the upstream dynamics of glyphosate production and trade can help to explain the logics and impacts of "off-farm capital" (Galt 2014), part of an industrial political ecology (e.g., Huber 2017) that can advance a broader pesticide research agenda.

To undertake this critical commodity study of glyphosate, we combine insights from Guthman's (2019) study of chemical-based agricultural assemblages with related insights from geographies of marketization. Drawing from science studies and political ecology, Guthman conceptualized biocides as material and ideological conditions of possibility for arrangements of firms, farms, labor, plants, soils, pathogens, and knowledge. Guthman reminded us that sociotechnical assemblages are always precarious achievements involving a tremendous amount of "stabilization work" that can only succeed temporarily. Each biotechnical "repair" creates new (or exacerbates old) problems, which then require renewed stabilization efforts: a version of "iatrogenic" harm requiring repair of repair. Yet the way elements of the assemblage co-evolve with each repair then constrains the possibilities for new repairs. Crucially, because knowledge is part of these assemblages, it, too, is constrained. Guthman (2019) aptly called this "technologies of repair [that] create ignorance about the problems they induce" (23). This aligns with Callon's (1998, 2007) notions of "framing" and "overflow." Framing assembles and entangles the large number of elements and agents that comprise commodity assemblages; for example, the elements necessary to produce herbicides, distribute them, and put them to use. Framing, however, is a delicate and incomplete process that can evade control, leading to "overflow." This inherent instability not only requires constant stabilization but can lead to crisis and efforts to reframe—to contain overflow—so that the entity in question can be stabilized again (see also Berndt and Boeckler 2020). The phenomenal growth of glyphosate clearly reflects this dynamic of stabilization and destabilization. The claims to effectiveness and safety that underpin glyphosate's ubiquity stabilized an herbicide assemblage that had been destabilized by the toxicity and selectivity of older herbicides, and it is glyphosate's ubiquity that is now eroding these claims. Yet how to repair the repair is unclear.

We argue that glyphosate's ubiquity and its emerging crises exist not only because of the transformation in agricultural practices initiated and developed with glyphosate but also because of the myriad ways in which off-farm production, markets, and trade of glyphosate itself shape the wider assemblage. We highlight the development aspirations of not only low- and middle-income farmers in the Global South but also agrochemical capital and the state. That is, the chemical ubiquity that characterizes the glyphosate assemblage is also a geography of uneven development comprising shifting firm networks, state policies, and changing trade relations. Our approach highlights marketization and commodification of glyphosate as a contradictory and always incomplete process driven by exclusions, devaluations, and more-than-economic logics that remake geographies of uneven development (see Werner 2016; Berndt, Peck, and Rantisi 2020; Berndt, Werner, and Fernández 2020).

In what follows, we examine glyphosate as a socionatural assemblage understood as a (spatial) arrangement of heterogeneous elements that entangle chemical substances, production technologies, agrochemical companies, and corporate strategies with crops, seed science, state regulation, and agricultural production methods (Guthman 2019). Our analysis is based on secondary literature in weed science and toxicology, official United Nations (UN) trade statistics, and proprietary industry data and reports (i.e., data from PMD). We map the emergence of the glyphosate assemblage over its fifty-year history, tied to changing agricultural practices, technologies, and knowledge struggles. We then discuss glyphosate discovery, the rollout of no-till methods in the 1980s, and the 1990s introduction of herbicide tolerant genetically modified (HT-GM) seed packages. We next analyze post-2000 patent expiry and how the mass production of glyphosate enables agrarian transition in the Global South and new south–south political economic relations of pesticide production and trade. Material overflows, interruptions, emergences such as cancers and superweeds, and knowledge struggles over these processes are interwoven through each of these phases and have shaped the resulting assemblage. We then cover the material dimensions and knowledge struggles around weed resistance and toxicity, theorizing how key agents work together to stabilize the global glyphosate assemblage at a time of crisis. In sum, we argue that the glyphosate assemblage has provided the conditions of possibility for the global expansion of high-yield chemical-intensive agriculture, and it is the current overflows and iatrogenic harms of the assemblage that have put it into crisis. Whether this leads to repairs that restore the assemblage or requires broader changes in these agrochemical geographies of uneven development remains to be seen.

The Making of the Glyphosate Assemblage: No-Till and HT-GM Seeds

Judging by sheer numbers, herbicides have been the clear success story of the agrochemical industry over the last half-century. The rise and availability of glyphosate has played an outsized role in this shift (Magin 2003; Zimdahl 2010). Globally, herbicide use has risen rapidly, comprising 42 percent of the global pesticide market by 2018 by value, far exceeding the share of insecticides (28 percent) and fungicides (27 percent; PMD 2019). The focus on herbicides as a class, however, obscures the key change in their use over time. Prior to the 1960s, herbicides were selective, targeted to broadleaf, grass, or woody species. Species selectivity did not translate into selective use per se. Indeed, the herbicide 2,4-D, a broadleaf biocide, inaugurated the weaponization of widespread herbicide application in war, first by the British in Malaysia and then by the United States in Vietnam, where it was mixed with 2,4,5-T to make Agent Orange. In the 1950s the British Imperial Chemical Industries synthesized and commercialized paraquat (and related diquat), the first nonselective herbicides, which shifted use from selective application for specific weed classes to general application for new no-till farming methods and land use change (e.g., land restoration for pasture or grazing; Zimdahl 2010). No-till farming allows for seeding directly after harvest or into fallow land without the need for plowing and harrowing. Often called *conservation tillage* by proponents, this reduces soil erosion and fuel-intensive mechanical tilling. Experiments in no-till farming using paraquat were underway in expansive farm systems in settler colonial contexts in the 1970s, and British aid programs liberally distributed paraquat to developing countries to lower labor expenditure (Grossman 1998; Wesseling, Corriols, and Bravo 2005). Broadcast application of paraquat and diquat over large land masses had limits due to the compounds' acute toxicity and environmental fate, however. Paraquat today remains a common pesticide used by small farmers in the Global South, is associated with thousands of deaths (mostly intentional), and has been banned in many countries (Grossman 1998; Wesseling et al. 2001; Wesseling, Corriols, and Bravo 2005; Pesticide Action Network [PAN] 2020).

Glyphosate enabled expansion of no-till farming methods. Discovered by a Swiss chemist in the 1950s, the novel compound changed hands several times but was not commercialized until a U.S. chemist at Monsanto discovered herbicide activity in variants of phosphonate derivatives from glycine in 1970. After successful lab and field trials, glyphosate was patented in 1971 and subsequently marketed by Monsanto under the trade name Roundup. Because of its high price, initially it was used mainly to control difficult perennial grasses (Magin 2003). As the price declined, however, it quickly displaced paraquat and diquat for no-till farming as the method expanded in the 1980s in the United States and subsequently in Latin America (mainly Brazil and Argentina).[1] In Brazil and Argentina, no-till farming was one of several critical technology changes prior to the introduction of HT-GM crops that pushed the agricultural frontier in the *cerrado* savanna region and the *gran chaco* ecosystem, respectively (Martínez Dougnac 2016; Cáceres 2018). In the United States, no-till methods facilitated by glyphosate together with machinery improvements led to a 30 percent decline in farm energy consumption in the 1980s and 1990s (Elmore 2018). Total global area of applied glyphosate increased to 70 million hectares by the mid-1990s, reflecting the expansion of no-till methods prior to the rollout of commercial HT-GM seeds (Woodburn 2000). Glyphosate would soon become synonymous with HT-GM seed packages, and no-till farming remained a significant practice that would form part of both GM farm systems and cereal and row crop farming more widely.

Glyphosate is a key element animating a wider sociotechnical assemblage that arranges specific agricultural production methods and biotechnological knowledge. Much has been written about Monsanto scientists' invention of GM crops and the establishment of the technological package with glyphosate, introduced commercially in the United States and

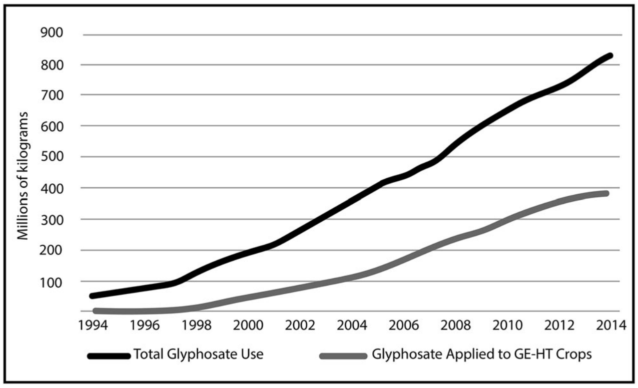

Figure 1. Total glyphosate use, 1994 through 2014. *Note:* GE-HT = genetically engineering herbicide tolerant. *Source:* Adapted from Benbrook (2016, S24).

Argentina in 1996. Elmore (2018) argued that this shift toward biotech on the part of Monsanto reflected a wider crisis in a chemical industry that had hitherto relied heavily on processing cheaply obtained petroleum by-products. In 1980, the company's net profits fell by half as knock-on effects of the oil shocks led to higher priced petroleum derivative compounds and forward integration by the oil majors seeking to profit from by-products (Elmore 2018). At the time, Monsanto was the largest and lowest cost producer of ammonium nitrate (fertilizer), and sold pesticides used widely in the U.S. Midwest (DDT, 2,4-D, 2,4,5-T, and parathions; Magin 2003). The company quickly divested from its own fossil fuel assets and production of these bulk, low-value "commodity chemicals" as it pivoted toward biotech development. The lead scientist of Monsanto's new biotech research effort told shareholders in 1982 that new products would be "less dependent on raw material costs" and would "have a strong proprietary character" (quoted in Elmore 2018, 162).

These efforts bore fruit by the mid-1990s, when Monsanto introduced HT-GM seeds that were branded as "Roundup Ready." Introduction of these glyphosate-tolerant soybean, maize, and cotton seeds in the key production regions of North America (the United States), Latin America (Brazil and Argentina), and East Asia (China and India) underpinned a highly potent sociotechnological assemblage that further spurred the dramatic growth of glyphosate use during the 2000s (see Figure 1). An additional effect was a further shift within the herbicide market away from competing broad-spectrum herbicides such as paraquat and even more so from more expensive selective substances such as urea-based herbicides (e.g., diuron used mainly for cotton). In particular, the separate and newer class of sulfonylureas that competed directly with glyphosate in the soybean and maize sector were severely curtailed by the triumphal march of the seed–glyphosate–no-till assemblage (Zimdahl 2010; PMD 2019). These heightened competitive tensions in the market forced agrochemical producers to redefine their strategic position vis-à-vis Monsanto. The replacement of numerous herbicides by glyphosate and glyphosate's entanglement with the lucrative GM seed market pushed an increasing number of agrochemical firms to shift their research and development (R&D) budgets from herbicide discovery to transgenic and hybrid seed trait development (Green 2018).

If Monsanto divested from many of its "commodity herbicides" in the 1980s, glyphosate remained its most profitable product and, in its various chemical forms, the compound drove vertically integrated expansion of manufacturing capacity. In the 1990s, the production of key intermediates was brought in-house, and the company increased extraction at its wholly owned phosphate mine in Soda Springs, Idaho (Woodburn 2000; Elmore 2018). The company maintained sufficient manufacturing capacity to supply the world market from five plants in the United States, Belgium, Malaysia, Brazil, and Argentina (Woodburn 2000).[2] Although Monsanto's installed capacity was significantly larger than competitor firms, the expiry of country-specific patents, licensing arrangements, and unlicensed generic production was well underway by the middle of the decade. Some thirteen manufacturers had installed capacities of 1,000 tons per year or more in 1998, based in Taiwan, Belgium, Denmark, Hungary, South Korea, Taiwan, and the United Kingdom. One large facility came online in China and significant additional production capacity was installed via a host of small firms (some twenty to forty in China; Woodburn 2000). The geography of glyphosate production, use, and the politics of value would radically shift in the new millennium, though.

Agrarian Transformations, Herbicide Production Networks, and New Uneven Geographies of Development

Central to the most recent chapter in the glyphosate assemblage is dramatic expansion not only in use but also production of herbicides in the Global

South and Eastern Europe. To be sure, agrochemical intensification has long been synonymous with the expansion of capitalist agriculture in the Global South. It has been part and parcel of mainstream development policy whether under state-promoted import substitution regimes advanced through the Green Revolution or subsequent structural adjustment and the formation of retail-driven agricultural commodity chains. In relation to this longer trajectory of appropriationism via chemicals (Goodman, Sorj, and Wilkinson 1987), today's glyphosate trends are marked by both global ubiquity—that is, the unprecedented volume of herbicide use—as well as striking new geographies of production, trade, and consumption.

A range of studies in diverse contexts have noted significant volume increases in herbicide use in the new millennium: a 50 percent increase in post-European Union (EU) enlargement member states (Bonanno et al. 2017), 250 percent in India (since 2005; Das Gupta et al. 2017), twenty-five-fold in China (Huang, Wang, and Xiao 2017), and twenty-fold in Ethiopia (Tamru et al. 2017). Several factors drive this "herbicide revolution" in middle-income countries (Haggblade et al. 2017). In the face of rising rural labor costs and off-farm employment in the Global South, use of inexpensive herbicides significantly lowers demand for costly, labor-intensive weeding (Gianessi 2013; see also Schreinemachers and Tipraqsa 2012; Hedlund, Longo, and York 2020). Herbicide use has also accelerated in Eastern European countries in the wake of the opening of markets after 1989, above all in Ukraine and Russia. This herbicide revolution has occurred even in many countries, including China, that have approved few HT-GM crops.[3] Thus, much of the increase reflects conventional application of glyphosate as a broad-spectrum weed killer between cropping cycles and in the expansion of no-till methods, and as HT-GM technologies continue to spread, one would expect even wider adoption (Benbrook 2016).

The observed herbicide revolution is not solely about rapid herbicide adoption but also comprises novel south–south and south-to-north production networks (see also Shattuck forthcoming). These new networks supply low-cost off-patent herbicides at high volumes, and glyphosate is chief among them. This fundamental reorientation of production networks to the Global South is perhaps the biggest surprise, given that conventional understandings in both mainstream and critical development literatures presume geographically stagnant North–South relations (Horner and Nadvi 2018). This shift is evident in official trade data, which show that global herbicide exports nearly quadrupled in volume from 2000 to 2017; this increase was 30 percent more than all other pesticide exports (UN COMTRADE 2020). "Emerging" market economies are now principal producers and exporters of herbicides. In 2018, four of the top ten global herbicide exporters (by volume) were "emerging" economies: China (1), India (5), Malaysia (7), and Ireland (10), followed by Argentina (11), Hungary (13), Poland (14), and South Africa (15; UN COMTRADE 2020). Among these countries, China and India stood out as significant exporters to both "emerging" and high-income countries for a range of pesticides, including both technical glyphosate (i.e., active ingredients [AIs]) and formulated products. Industry sources estimate that more than 2,500 pesticide manufacturers were operating in China in 2013, producing more than 300 AIs and 3,000 formulations (Han 2014). Quite strikingly, China accounted for 46 percent of all herbicide global exports in 2018, whereas the United States, the second largest exporter, accounted for just 9 percent (UN COMTRADE 2020).

This concentration of productive capacity in China is the outcome of a more complex story of industry restructuring and production network rearrangements over the previous two decades. A turning point for expanded herbicide use was the year 2000, when Monsanto's final patent on glyphosate expired and generic producers expanded production of glyphosate AI and formulated new, cheaper glyphosate-based herbicides (GBHs).[4] As one would expect, this had immediate downward effects on global prices. At the same time, having adopted measures to reduce production costs in anticipation of generic competition, Monsanto continued to manufacture AI and branded formulas as a "proprietary off-patent producer." The extent to which prices fell can be illustrated in Argentina, where the glyphosate patent expired early, in 1987. Prices dropped from US$40 per liter in the early 1980s to around US$10 in the early 1990s to US$3 in 2000 (Trigo et al. 2003). Sales of glyphosate soared as a result (Figure 2), mirroring the spectacular volume increases noted earlier, until the Great Recession in 2008 and 2009, which started a period of volatility in both sales and prices linked to

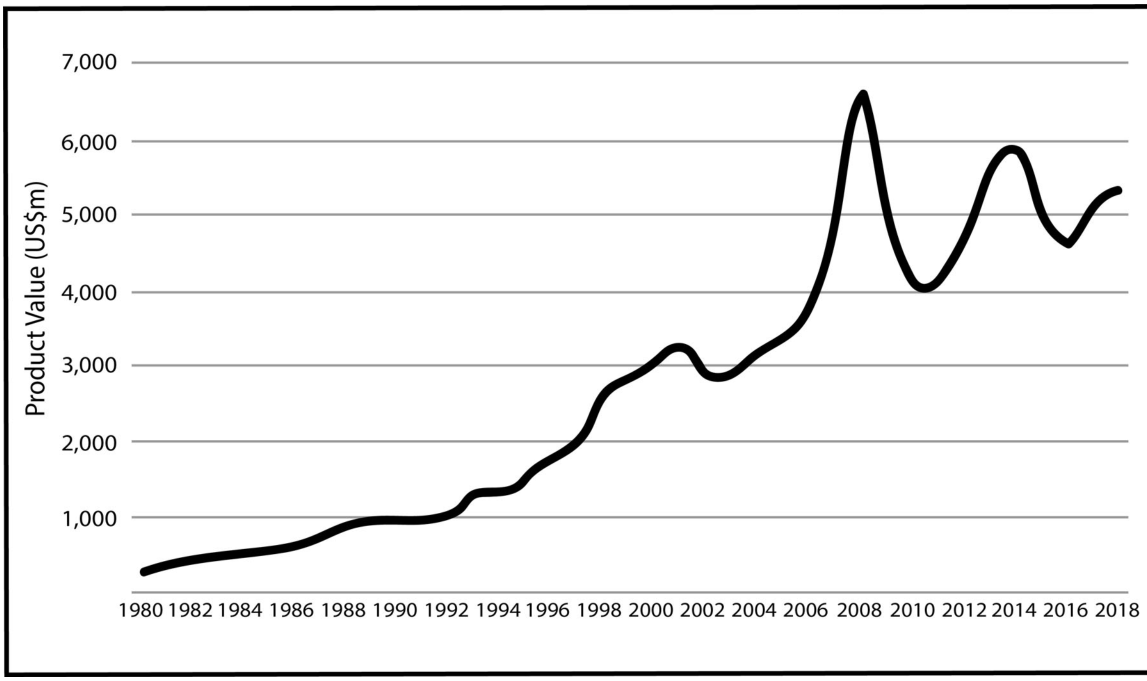

Figure 2. Global glyphosate sales, 1980 through 2018. *Source:* Adapted from data provided in communication with Phillips McDougall.

variability in both crop markets and Chinese production of technical glyphosate (Shoham 2015). Emerging at that time, too, were new challenges to the safety-effectiveness promise of the benign biocide, to which we return in the next section.

Glyphosate's transformation from a patent-protected product into a "market commodity" necessitated a profound rearticulation of global networks of production, distribution, and use. The availability of cheaper products led to increasing demand in more price-sensitive "emerging" markets where generics account for a growing proportion of overall pesticide consumption. This provided a window of opportunity for second- and third-tier companies, either selling directly into these markets or profiting from cost-cutting strategies of former patent-holding first-tier firms (e.g., outsourcing, licensing, divesting; Skernivitz 2019). Firms from China and, to a lesser extent, India have played a dominant—and changing—role in this shifting organizational and spatial division of labor.

Initially, production capacities in China and other "emerging" countries were used to acquire technical AI and intermediate products at lower prices in captive supplier relations, termed "toll manufacturing" in the industry. Some of the larger generic companies such as U.S.-based Arysta LifeScience (now owned by Indian company UPL) and the Israeli generics firm Makhteshim Agan Industries (acquired by ChemChina and rebranded as Adama) adopted this asset-light approach to outsourcing production to smaller companies in China (and later also in India). Chinese exports were thus dominated by the less profitable "raw material" in agrochemical supply chains, almost exclusively consisting of generic AIs. Coinciding with the expiration of Monsanto's patent for glyphosate, the Chinese national government facilitated this development with a discriminatory export tax rebate program on key pesticide products to give producers a favorable position in the global market. "Pure" AIs received higher rebates than formulations, providing importing international companies with inexpensive material that could be reprocessed into higher value formulations and exported with a considerable profit margin. Together with low-wage labor, ready availability of capital, and relatively lax environmental standards, this quickly positioned China's pesticide industry as the key supplier of off-patent herbicide AIs globally (ChinaAg 2018).

After Chinese companies had become indispensable suppliers of low-value "commodity chemicals," the Chinese state switched tactics and embarked on a strategy of upgrading in the early 2010s. The strategy coincided with global overproduction and a price slump for glyphosate after the financial crisis and

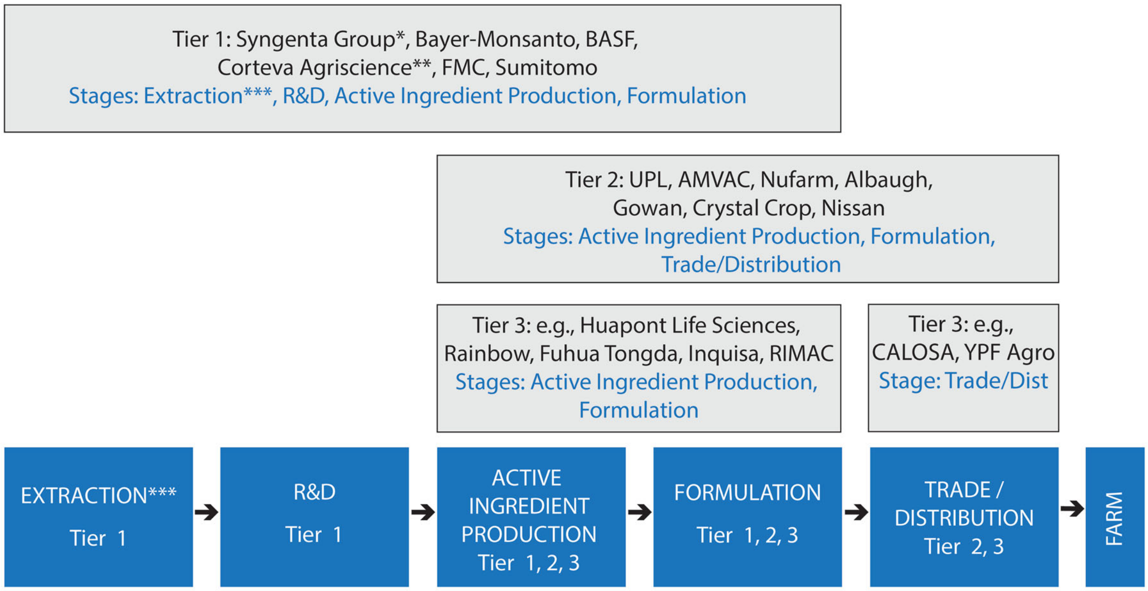

Figure 3. Schematic representation of the generic herbicide production network. *Note:* *Includes ChemChina, Sinochem, Adama. **Dow/DuPont. ***Agrochemical firms' relation to resource extraction requires further research. On Bayer-Monsanto ownership of an elemental phosphate mine, see Elmore (2018).

dovetailed with China's "going out" strategy, wherein upgrading of domestic production capacity was coupled with significant outward foreign direct investment (McMichael 2020). The Chinese government sought a considerable reduction in the number of agrochemical firms and consolidation of a small number of internationally competitive pesticide companies or, better, large conglomerates. State-led restructuring connected with three key upgrading objectives that were at least partially achieved: (1) increasing exports of finished, formulated products vis-à-vis AIs; (2) targeting high-end users in the EU and North America; and (3) building up brands and shifting away from mere quantity-oriented exports (Han 2014). Connected with these shifts, the state introduced tighter environmental regulations that led to a crackdown on smaller manufacturers, closures, and forced mergers and relocations. Taken together, these practices reduced Chinese glyphosate AI production capacity from around 940,000 tons in 2014 to about 725,000 tons in 2018, slowing glyphosate export growth and raising prices globally. To put Chinese glyphosate capacity in perspective, in 2016 China was still estimated to account for roughly 70 percent of global glyphosate production (ChinaAg 2018; PMD 2019; Rana 2020).

China's pesticide sector restructuring also sparked global reorganization of the industry. Overall price fluctuations, generic competition, and the ups and downs in key agricultural commodity markets led to a flurry of mergers and acquisitions (M&As) in the agrochemical industry. By 2015, the number of first-tier firms was down to six; since then, further M&As reduced that number to only four global firms: Syngenta Group (dominated by ChemChina), Bayer-Monsanto, Corteva Agriscience (merger between Dow and DuPont), and BASF. The takeover of Syngenta by ChemChina was the largest merger in Chinese history. On the heels of these widely reported M&As, a group of second-tier companies consolidated, including Sumitomo Chemical (Japan), Nufarm (Australia), FMC Corporation (United States), United Phosphorous Limited (India), and several Chinese companies including Nutrichem, Red Sun, Shandong Weifang Rainbow, and Yangnong. A larger number of specialized companies comprise a third tier, including firms in a continuously evolving landscape of technical-grade producers and formulators in China, India, and other "emerging" economies. These firms include Huapont Life Sciences, Fuhua Tongda, Jiangsu Huifeng, Sichuan Leshan Fuhua, Wynca, Lier, and Kumiai Chemical (ChinaAg 2018; PMD 2019; see Figure 3). Herbicides, mainly glyphosate, play the most significant role in the portfolios of these third-tier Chinese companies.

These M&As and accompanying disinvestments resulted in shifts in supply chains that remake geographies of uneven development. The strategic repositioning of the sector in China already discussed provided an opportunity for Indian companies to occupy the lower tiers of the network. Indian agrochemical production subsequently rose by 64 percent from 2007 to 2017 (Shan 2019). In addition to UPL, smaller players such as Coromandel, Punjab Chemicals, and Indogulf positioned themselves to benefit by taking on production in the wake of rising production costs, tighter regulations, and state-driven consolidation in China. As a result, Indian producers increased their exports to other Asian markets, Latin America, and Africa, by nearly threefold between 2012 and 2017 (UN COMTRADE 2020). Apart from being one of the fastest growing agrochemical markets itself, Indian producers are used by Chinese companies as alternate sources of technical and intermediate products and collaborate in the development of new products and formulations (PMD 2012; Shan 2019). Thus, a complex pattern has emerged globally where products (AI and formulations) shifted between firms at different tiers regionally, involving divestments and acquisitions as well as cooperative licensing, cascading outsourcing agreements, and the indirect and direct control of marketing channels in key regions such as Latin America.

Our analysis of industry and trade reports points to three key trends in the recent development of the herbicide production network. First, AI production activities have largely shifted toward the Global South, with China being the key destination and India playing an increasingly prominent role. This has been accompanied by a flurry of transactions in which established companies sell older substances to smaller generic firms that have a larger production presence in these countries. In these transactions, substances change hands repeatedly, including many identified as highly hazardous by institutions such as the PAN.[5] These divestments normally include registrations, manufacturing information, and intellectual property rights (Euromonitor International 2016; PMD 2019). Second, the upgrading process undertaken by Chinese capital led to specialization in more advanced AI production and formulation and acquisition of knowledge via investment in key global generic companies. Moves such as ChemChina's acquisition of Makhteshim (now Adama) were paralleled by other companies such as Japan's Sumitomo acquisition of a majority share in the Indian company Excel Crop Care and the Indian company UPL's purchase of Arysta Life Science in the United States. These M&As regularly involved a shift of production "southward." In the case of Adama, for example, Chinese facilities became the center hub for AI manufacture and formulation following the company's takeover by ChemChina (PMD 2019). Third, although R&D-driven companies account for a majority share of the agrochemical market (59 percent), they compete directly with generic firms as the proportion of off-patent AIs now far exceeds those under patent due to the paralysis in new discoveries (PMD 2019). Viewed through this lens, the glyphosate assemblage is sustained organizationally by a host of networked second- and third-tier firms that have relied on the production of AI and, increasingly, GBH formulations to enter a rapidly expanding generics market. The assemblage furnishes the material conditions (low cost, abundant supply) for agrarian change, as glyphosate enables labor replacement in the Global South and Eastern Europe, in turn producing a global geography of chemical ubiquity.

Chemical Geographies and Nature's Liveliness

Throughout its breathtaking history, glyphosate's success as a broad-based herbicide rested on the promise of ever-increasing efficiency and productivity with little or no risk. Paradoxically, glyphosate's popularity was due to both its ability to kill multiple types of weeds and its purported safety for human and nonhuman organisms as well as the environment generally. Proponents declared that as part of no-till systems and when packaged with GM seeds, glyphosate was better for the soil and was more efficient because farmers could now spray during the growing season, killing everything but the desired crop. Efficiency, in turn, seemed to enhance safety, because selective herbicides and more toxic nonselective compounds could be substituted by this single, apparently benign, biocide (Cuhra, Bøhn, and Cuhra 2016). The construction of a benign biocide combined with its low cost led to the expansion of uses of GBHs: for desiccation as a "harvest aid" on cereal crops, sugarcane, and legumes; to clear land between trees in orchards; to clear waterways of invasive plant species; to remove nonwoody brush from roadsides and railways; and to control weeds in urban settings like parks and schools (Cuhra, Bøhn, and Cuhra 2016; Van Bruggen et al. 2018).

Table 1. Leading herbicides in 2018

Rank	Active ingredient	Sales ($ million)	Launch date	Main company
1	Glyphosate	5,325	1972	Bayer
2	Glufosinate	916	1986	BASF
3	Mesotrione	780	2001	Syngenta
4	2,4-D	748	1945	Nufarm
5	Atrazine	655	1957	Syngenta
6	Metochlor	645	1975	Syngenta
7	Paraquat	585	1962	Syngenta
8	Acetochlor	475	1985	Bayer
9	Pinoxaden	435	2006	Syngenta
10	Pendimethalin	405	1976	BASF
11	Dicamba	388	1965	BASF
12	Flumioxazin	380	1993	Sumitomo
13	Clomazone	365	1986	FMC
14	Picloram	310	1963	Dow
15	Clethodim	309	1987	Sumitomo

Note: Adapted from Phillips McDougall (2019).

Although dissident scientists long challenged these claims and the chemical's pervasive use that they supported, only in the last decade have we seen the erosion of the dual promise of glyphosate's efficiency and safety. Drawing on the emerging attention to chemical geographies, we extend that lens to encompass the materiality of glyphosate itself, addressing how it acts on plants' evolutionary ability to develop resistance and how exposure affects human health, including its links to cancer and endocrine disruption. The instability of the glyphosate assemblage from these overflows and iatrogenic harms illustrates the ways in which the dual promise of efficiency and safety is yielding a dual crisis of weed resistance and health problems; that is, it illustrates the limits of repair, as new problems emerge as an effect of interactions within the assemblage.

Weed Resistance

As biocides, herbicides appropriate not only material resources and energy needed for production but also pest plants' biological susceptibility to these chemicals (Jørgensen et al. 2018). In turn, however, plants evolve under the selective pressure of these herbicides, yielding herbicide resistance. This erosion of susceptibility then spurs the well-documented "pesticide treadmill," as new-generation biocides replace older compounds that have lost their effectiveness (Zimdahl 2010; Swinton and Van Deynze 2017; Green 2018; Heap and Duke 2018). Glyphosate itself is a result of this process, in which the iatrogenic problems of one repair require further repair while also locking in the chemical paradigm. When Monsanto introduced glyphosate in 1972, it replaced both nonselective herbicides and several selective herbicides that suffered from declining effectiveness due to widespread weed resistance. Today, however, weed scientists lament that no new modes of action have been commercialized in thirty years (Heap and Duke 2018). As Table 1 shows, only three of the top fifteen herbicides in 2018 were developed after 1990; the two developed in the 2000s are for selective herbicides, and the number four herbicide is 2,4-D, an agrochemical mainstay since the 1940s. Meanwhile, the herbicide resistance cycle, or the time in which weed resistance significantly undercuts herbicide effectivity, has decreased. Some experts speculate that this "biological" turnover time for weed resistance stands at only six to seven years (Green 2018).

Weed science optimists predicted that glyphosate would not provoke significant development of weed resistance because, unlike most other herbicide modes of action, resistance did not occur in wild plant populations (Heap and Duke 2018). Moreover, glyphosate resistance appeared to be difficult to acquire through known pathways. Whereas in some herbicides, a mutation in just one base pair can confer upwards of tenfold resistance and many single base pair mutations can lead to this result, in glyphosate very few single base pair mutations lead to any significant level of resistance (Heap and Duke 2018). This optimism soon faded. Indeed, the same year that Monsanto introduced Roundup Ready soybeans in the United States and Argentina (1996), the first case of evolved glyphosate resistance was recorded in Australia in the grass *Lolium rigidum*, found in an apple orchard that had been treated with a GBH multiple times per year for fifteen years. From a weed science perspective, the introduction of HT-GM crops created the perfect conditions for weed resistance because selection took place over greater land areas and for longer periods of time than any other herbicide class (Heap and Duke 2018). To date, weed scientists have reported forty-eight glyphosate-resistant plant species, including species that are resistant to glyphosate alone and those that possess resistance traits for multiple herbicides, in twenty-seven countries (Heap 2020).

The scope of weed resistance mechanisms is also significant. If single base pair mutations lend low levels of resistance to glyphosate, double base pair alterations are far more effective. These and other genetic changes (i.e., codon deletion and gene amplification) lead to resistance at the target site, rendering the target enzyme (EPSPS) resistant to glyphosate. Because glyphosate was developed for commercial use in HT-GM crops, Monsanto scientists argued that double mutations could not be transferred from cultivated GM crops to wild plants because the mutations would have to be developed simultaneously (Green 2018; Heap and Duke 2018). They were wrong. Weeds did develop double mutations but did so in sequence: The low level of resistance conferred by a single genotypic change allowed enough plants to survive and later to develop the second mutation. The adoption of multiple resistance traits is called *creeping resistance* and stems from the application of low doses of glyphosate. The progeny of plants with low-level resistance combine traits, leading to the building up of higher levels of resistance. The solution has been to apply higher doses of glyphosate to maximize the kill rate. This strategy has failed with several grasses, which account for nearly half of all glyphosate-resistant weeds, where high-dose applications coexist with high weed resistance rates (Heap and Duke 2018). Plants have also developed unique nontarget site forms of glyphosate resistance to inhibit the compound's translocation from sprayed leaves to meristems. Scientists are just beginning to study the mechanisms weeds have developed that limit the translocation of the compound, including changing the leaf shape to absorb less herbicide spray and sequestering the compound in epidermal tissue to prevent or minimize translocation. Plants also have developed a form of resistance that weed scientists call the Phoenix phenomenon. Observed in *Ambrosia trifida*, the giant ragweed, the leaves of the plant die within hours of treatment rather than the normal systemic effect, which usually takes days. Because the compound is trapped in the dead leaves, the plant subsequently regrows, rising from the biocidal ashes (Heap and Duke 2018).

The failures of weed scientists and agrochemical researchers to predict and solve the problem of resistance illustrate Guthman's (2019) points about knowledge as part of the agrochemical assemblage. Not only is knowledge constrained by the assemblage but rising weed resistance has already had an enormous impact on the herbicide commodity network. Bayer (Monsanto) and Corteva AgriScience have developed and marketed new HT-GM seed packages with stacked traits, combining glyphosate with either dicamba or 2,4-D tolerance, respectively (Birkett 2020a, 2020b). Bayer and BASF have even teamed up to introduce a triple-stack soybean line combining resistance against glyphosate, glufosinate, and dicamba (Bird 2020). In addition to this, nonglyphosate HT-GM packages have been introduced that stack traits resistant to other herbicides in soybeans and other crops (Bayer: glufosinate and isoxaflutole; Syngenta: dicamba and s-metolachlor; FMC: sulfentrazone and pyroxasulfone; Birkett 2018; PMD 2020a). In 2020, Bayer also announced early phase development of the first new herbicide mode of action in thirty years targeting grasses, precisely the weed class that has developed most resistance to glyphosate (Birkett 2020a), and the promise of biopesticides also looms large. In other words, institutional lock-in has meant that the herbicide treadmill is powered by new combinations more than new discoveries of either new chemicals or alternatives to chemicals.

Although it might be tempting to see this as a terminal crisis for agrochemicals, the dialectical dynamics of this crisis, on the one hand, and the herbicide revolution in the Global South and Eastern Europe, on the other, suggest that these limits will also yield surprises and opportunities for new forms of capital accumulation in and through herbicide production networks (Boyd, Prudham, and Schurman 2001; Mansfield 2011; Guthman 2019). Indeed, there is significant *expansion and opportunity* in the generic market as second- and third-tier chemical producers innovate at the level of process and formulation to increase the number of herbicides on offer while maintaining low price points. The second-tier Chinese firm Jiangsu Yangnong (annual sales of $700 million), for example, has recently added dicamba to its product line to meet demand for stacked trait HT-GM crops and alternatives to glyphosate for resistant weeds (PMD 2020b). Although glyphosate accounts for 40 percent of U.S.-based Albaugh sales, the company, with subsidiaries in Argentina, Brazil, and Mexico and nearly half of its sales in Latin America, has boosted production of 2,4-D and dicamba, and launched new selective herbicide formulations (PMD 2019). Chemical producers can also seek new markets, where glyphosate resistance is not yet a major problem, and, indeed, Latin American producers are doing so in Central America (PMD 2019). In general, formulators of generic GBHs are in an advantageous position, especially given that loss of patent protection for existing AIs coincides with the absence of new AI discoveries. In fact, Albaugh's "new" position in 2,4-D is a return to its roots, now with a global twist: The company's first formulation plant in Ankeny, Iowa, was a major producer of 2,4-D for the U.S. Midwest in the 1980s.

Health and Safety

In addition to efficiency, safety was the other half of the paired promise that permitted the pervasiveness of glyphosate. Just as its very pervasiveness clearly accelerated the development of weed resistance, recent concerns over glyphosate safety to humans raise issues about pervasive chemicals and emergences in humans and nonplant organisms. The WHO's reclassification of glyphosate as "probably carcinogenic to humans" stands in sharp contrast to Monsanto's long-standing claims of low toxicity and environmental benignancy, backed by regulatory agencies (International Agency for Research on Cancer 2017). Following the WHO's assessment, both the U.S. Environmental Protection Agency (EPA) and the European Food Safety Authority made highly controversial moves, reaffirming their assessments that glyphosate is noncarcinogenic (Cuhra, Bøhn, and Cuhra 2016; Myers et al. 2016; Benbrook 2019). In 2020—as we were writing this article—the EPA again backed glyphosate, asserting that there is no risk to human health and minimal environmental risk (EPA 2020). The EPA's latest claims about the safety of glyphosate apparently discount new evidence about the link between glyphosate and cancer, mainly non-Hodgkins lymphoma (Zhang et al. 2019; Portier 2020), as well as between glyphosate and noncancer outcomes; for example, in the kidneys, liver, and gastrointestinal system (see Agency for Toxic Substances and Disease Registry 2019). New studies also are finding that glyphosate acts epigenetically and as an endocrine disruptor to produce long-term reproductive and developmental effects (Duforestel et al. 2019; Kubsad et al. 2019; Teleken et al. 2020). Notably, the U.S. EPA's assessment also contrasts with that of the U.S. Centers for Disease Control, which confirms that there are both cancer and noncancer risks to human health (Agency for Toxic Substances and Disease Registry 2019). These conflicting findings are then fueling ongoing legal actions in numerous jurisdictions over the compound's environmental and health risks. The first successful lawsuit against Bayer/Monsanto over glyphosate exposure concluded in 2018, when a jury awarded DeWayne Johnson a staggering $289 million (Gillam 2018). Since then, numerous individual and class action suits have been filed against the company in the United States and around the world (Houston 2019; Labin 2019; U.S. Right to Know n.d.).

Adding another layer of complication, glyphosate has been presumed safe based on claims that it does not persist in the environment but rapidly breaks down to nonbiocidal compounds, even though not a lot is known about the actual fate and persistence of either glyphosate or its metabolites. Reflecting ways in which knowledge is internal to the assemblage, this knowledge gap exists in part because GBHs are classified as nontoxic. That is, because GBHs are considered safe, governmental agencies do not regularly test agricultural land or food products for residues. Despite lack of systematic testing, studies have discovered glyphosate's remarkable pervasiveness in soil, the human microbiome, food, and water (Battaglin and Kolok 2014; Bai and Ogbourne 2016; Cuhra, Bøhn, and Cuhra 2016; Myers et al. 2016; Van Bruggen et al. 2018). In the 2000s, the U.S. Geological Survey found low levels of glyphosate or its principal metabolite (AMPA) in 58 percent of nearly 4,000 soil and water samples from thirty-eight states. The first global-scale model of environmental hazard found glyphosate and AMPA to be low-level, persistent contaminants in about 93 percent of croplands, reaching middle to high hazard levels for about 1 percent of global cropland (Maggi et al. 2020). Occasional food testing in the United States and Canada has revealed widespread presence of glyphosate and its principal metabolite (Bai and Ogbourne 2016; Benbrook 2016). To date, however, findings on residue levels have not led to prohibitive regulatory actions. Instead, in 1999, 2012, and 2015, the EPA *increased* tolerance levels (i.e., allowable residues) in cereals and feed crops between 15 and 600 percent (Benbrook 2016).

Despite assurances of safety from the industry and regulatory agencies, the 2015 WHO determination of GBHs as probable carcinogens and the recent rulings against Monsanto in legal cases have placed glyphosate at the center of public concern over pesticides, yielding a growing patchwork of regulations at multiple scales. Examples include temporary suspension (e.g., the University of California system), bans on urban use, bans on postemergent application (state of Andhra Pradesh, India), suspensions of new GBH registrations (Vietnam), and a ban on imports (Sri Lanka). Uncertainty surrounding glyphosate's license in the EU also remains a key factor. Although the number of multiscale regulatory actions against glyphosate is increasing, agrochemical firms, as we have discussed, are not abandoning glyphosate but rather are creating new formulations of existing active ingredients including glyphosate for agricultural use. By combining glyphosate with herbicides of high toxicity, the priority of safety, already under considerable strain, is sacrificed to the altar of efficiency.

Conclusion

The promise of a benign biocide appears to be too good to be true. The unraveling of that promise, however, cannot be properly understood without recourse to the wider set of social and natural relations that have been articulated in and through glyphosate. We have seen how the compound's transition from a boutique, high-priced weed solution to the world's cheapest and most ubiquitous herbicide was tied initially to the expansion of no-till agricultural methods with the promise of better soil health and lower emissions. The introduction of HT-GM seed packages furthered this transformation in tandem with wider changes in agricultural practices in the Global South as glyphosate offered a readily accessible solution to rising rural labor costs. As GBHs replaced diverse weed management techniques, including multiple herbicides, the compound was used ubiquitously across massive swaths of terrain.

Our argument has been that understanding these dynamics in agriculture requires that we consider the interactions among upstream chemical industries as part of human–nature assemblages. By shifting our lens to the generic herbicide industry, we have detailed the rapid growth and restructuring of its production network, which has met demand with low-cost formulations. Centered in China, third-tier firms marshaled glyphosate manufacturing into a network entry strategy. Regulatory enforcement and policies to promote product and process upgrading led to a reorganization of firms and their relationships, yielding considerable consolidation not only among top-tier R&D firms but also among generic AI producers and formulators, as some production moved from China to India and elsewhere.

What are the implications of our arguments about the glyphosate assemblage for how we think about chemically driven industrial agriculture? Some see a capitalist system of food production in crisis that has finally passed a tipping point. For historical geographer Moore (2015), for instance, superweeds sound the death knell for an agrifood system centered around "cheap food." Noting diminishing returns to productivity with each modern innovation wave, Moore argued that the cycles of capital intensification in food production that facilitated soaring yields and unprecedented declines in food prices in the twentieth century have reached their limits in the twenty-first century. The stubborn persistence of industry insiders and protagonists who continue to espouse modernist logics of repair and technical engineering might be last gasps for a system in terminal crisis. This is not our conclusion, however; our analysis of the glyphosate assemblage suggests that claims like these are premature at best. Global pesticide markets and the vast majority of AI substance sales continue to grow, not least because—as we have shown—weed resistance provides new profit and accumulation opportunities as older AI substances enjoy a comeback in mixed herbicide formulations and stacked-trait HT-GM seeds. As in Guthman's (2019) analysis, it is precisely these multiple entanglements under conditions of chemical ubiquity that illustrate the limits to modernist (re)framings of agrochemical-intensive agriculture as either in terminal crisis or capable of endless technological fixes. Instead of stylized conclusions like these, we have conceptualized glyphosate as a key element animating a wider socio-technical assemblage that arranges specific agricultural production methods and biotechnological knowledge. From such an assemblage perspective, we focused on contradictory disentanglements to better come to terms with glyphosate's chemical ubiquity and resulting uncertainties and anxieties. Doing so requires recognition that agrochemicals are commodities in their own right (rather than just production inputs) and, as such, are active agents that (re)arrange heterogeneous elements in deeply contradictory ways, creating both the material conditions for market success as well as putting this success in danger.

Our interrogation of the glyphosate assemblage suggests that a fruitful and underexplored dialogue is in order across scholarship focused on the socionatures of pesticides and other chemical geographies and on the study of changing geographies of global production. If chemicals like glyphosate are ubiquitous, the production of this ubiquity results from the interaction between sociotechnical knowledge, human–environment and more-than-human natures, and the policies and plans of competitive capitals and states. Glyphosate's transformation from protected intellectual property to a global market commodity has coincided with the disruption of a long-standing pesticide geography in which agrochemicals were largely produced (and consumed) in the Global North and exported to countries in the Global South. In the new map of chemical ubiquity, middle-income countries are also principal producers, exporters, and end markets in a geography characterized by new south–south dynamics. By linking chemical ubiquity to shifting firm networks, our focus on the glyphosate assemblage highlights that marketization and commodification of glyphosate are deeply contradictory and always incomplete. Although these production dynamics are formally outside institutions of repair such as weed science, learning to think across these dimensions can aid in understanding how the limits of repair will run their course. As the regulatory landscape for glyphosate shifts and both generic production and use expand rapidly in the Global South, clearly a more global, transdisciplinary approach can grasp the associated risks and opportunities across a highly dynamic geography of uneven development.

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Notes

1. End-user prices varied considerably in different countries. Averaged across major country markets, Woodburn (2000) documented a decrease from US$33.99/kg of technical glyphosate to US$22.12/kg between 1991 and 1997
2. Although Monsanto's precise installed capacity was unavailable, Woodburn (2000) recorded that Monsanto had an annual capacity to produce at least 140,000 tons of the key intermediate phosphorous trichloride at its Luling, Louisiana, facility in the mid-1990s.
3. China is a major producer of HT-GM cotton but the only other GM crop the government has approved is papaya (Foreign Agricultural Service Staff 2017).
4. Generic producers are normally defined as firms that manufacture AIs or formulations that were researched, developed, or first introduced by another company and attribute the majority of their sales to products that are off-patent.
5. A recent example is the AI metsulfuron-methyl. This herbicide was sold by DuPont to FMC in 2017 in the wake of DuPont's merger with Dow, with FMC quickly passing the substance on to the Indian company Crystal in 2018. Metsulfuron is a selective sulfonylurea herbicide introduced by DuPont in 1984 and mainly used for cereals, rice, and sugar-cane. It was on the PAN list of highly hazardous pesticides from 2011 to 2013 and is currently banned in China.

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