Agriculture and Human Values
https://doi.org/10.1007/s10460-023-10492-w

DISCUSSION PIECE

A new critical social science research agenda on pesticides

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Accepted: 8 July 2023

Abstract

The global pesticide complex has transformed over the past two decades, but social science research has not kept pace. The rise of an enormous generics sector, shifts in geographies of pesticide production, and dynamics of agrarian change have led to more pesticide use, expanding to farm systems that hitherto used few such inputs. Declining effectiveness due to pesticide resistance and anemic institutional support for non-chemical alternatives also have driven intensification in conventional systems. As an inter-disciplinary network of pesticide scholars, we seek to renew the social science research agenda on pesticides to better understand this suite of contemporary changes. To identify research priorities, challenges, and opportunities, we develop the pesticide complex as a heuristic device to highlight the reciprocal and iterative interactions among agricultural practice, the agrochemical industry, civil society-shaped regulatory actions, and contested knowledge of toxicity. Ultimately, collaborations among social scientists and across the social and biophysical sciences can illuminate recent transformations and their uneven socioecological effects. A reinvigorated critical scholarship that embraces the multifaceted nature of pesticides can identify the social and ecological constraints that drive pesticide use and support alternatives to chemically driven industrial agriculture.

Keywords Pesticides · Global pesticide complex · Pesticide industry · Pesticide regulation · Pesticide toxicity · Pesticide social science research agenda

Abbreviations

AI	Active ingredient
DDT	Dichlorodiphenyltrichloroethane
EPA	Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization
GM	Genetically Modified
HT	Herbicide Tolerant
IPR	Intellectual Property Rights
MT	Metric Tons
PAN	Pesticide Action Network
POPs	Persistent Organic Pollutants
R&D	Research and Development
UN	United Nations
UNEP	United Nations Environment Programme
US	United States
WHO	World Health Organization

Introduction

Synthetic pesticides are at the heart of food production in much of the world today. As conventional, industrial farming has expanded, pesticide use has increased dramatically (Schreinemachers & Tipraqsa 2012). Synthetic chemical input into the environment, of which pesticides make up the largest volume, has grown faster in the last 50 years than any other single driver of global environmental change including greenhouse gas emissions (Bernhardt et al. 2017). Globally, imports of formulated pesticides — including herbicides, fungicides/bactericides, insecticides/acaricides,

The authors of this paper are all part of the Pesticide Research Network (PRN). The PRN was founded in 2021 as a research collaborative that is interdisciplinary, international, and includes civil society and academic researchers.

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and nematicides — nearly doubled from 2.5 million metric tons (MT) in 2005 to 4.8 million MT in 2019 (Shattuck et al. 2023). The drivers of these trends are complex and intersecting. Long dominated by large transnational corporations seated in the global North, recent years have seen both corporate consolidation and the emergence of complex supply chains driven in part by a generics revolution. By 2018, the market share by sales of proprietary pesticides reached its lowest level ever, just 15% of sales compared to 30% in 2000 (IHS Markit 2020a). Bolstered by manufacture of generics, China has become the world's principal exporter of pesticides (33% by volume), followed by India (9%) (Stobbart and Rana 2022). This represents a massive shift for a sector that was long dominated by the US, Japan, and Western Europe, which together accounted for 75% of global pesticide use and the bulk of production in the 1980s (WHO and UNEP 1990). Today, the US and Germany each represent only 7% of the volume of world exports (Stobbart and Rana 2022). Lower prices, high demand, and socio-ecological forms of lock-in drive intensified pesticide use in places long dependent on these inputs, while agrochemicals have become more widely accessible to farmers who previously deployed few if any at all.

With 1.8 billion people in the world engaged in agriculture (Alavanja 2009), this intensification of agrochemical use raises urgent questions about the myriad ways these chemicals alter environments and social lives. A growing body of academic and non-academic literature demonstrates pesticides' harms to ecological and human health and well-being (e.g., Rezende et al. 2021). The move to ban or restrict older, more acutely toxic pesticides gave rise to next-generation compounds, but promises of their safety, too, have in many cases been eroded by scientific research on toxicants. Pesticide resistance remains a long-standing problem, as weeds, insects and pathogens develop resistance especially to the most widely used chemicals. Yet a dearth of new chemistries to replace compounds as they become less effective has led to the revival of older compounds that are often more residual or more acutely toxic. In the face of these intertwined challenges, pitched battles over how to regulate pesticides continue. The terrain of those contests is also shifting as some local jurisdictions restrict use based on new scientific findings yet to be acknowledged by national regulators. Paradoxically, decades of such material, social, and political challenges to the model of chemical-intensive agriculture have coincided with its consolidation and expansion.

Social science research on pesticides has not kept pace with these remarkable changes in pesticide use, corporate structure, supply chains, and the generic market revolution, and the recursive interactions with environmental, labor, and consumer movements; regulation; technology; and scientific knowledge. In the 1970 and 1980 s, a robust social science research agenda emerged in the wake of movements to ban acutely toxic pesticides (e.g., Boardman 1986; Wright 1986; Thrupp 1988). This agenda enhanced empirical understanding of the linked social and environmental effects of pesticides while also contributing to the development of political ecology and environmental justice research and advocacy frameworks. Research consolidated around topics such as the political economy of international pesticide regulation and trade, the Green Revolution and similar development policies, and the deleterious health effects of acutely toxic or other hazardous exposures on plantation workers, small farmers, and downstream and downwind communities. Case study research on pesticides and their role in agrarian change continued, but by the early 2000s the broader social science agenda on industrial agriculture was eclipsed by attention to alternatives, including organic and fair trade certification, agroecology, and urban farming (Galt 2014).

The new social science research agenda that we develop here responds to 21st century dynamics of "the global pesticide complex" (Galt 2008), a term that serves as a heuristic device to identify interactions among the pesticide industry's emerging global division of labor, the recursive effects of pesticide regulations, and changing paradigms of toxicity shaped by new understandings of chemical exposures (see Table 1). We proceed in three corresponding sections. In the second section, we introduce the global pesticide complex and begin to trace its dimensions through dynamics reshaping the agrochemical industry. In the third section, we consider how existing bans and regulations emerged from research and advocacy and how they have generated iterative effects, or what we call "regulatory afterlives," that merit renewed attention. In the fourth section, we lay out how changing paradigms of toxicity and the politics of evidence trouble regulatory action, shape the agrochemical industry, and demand expansive understandings of harm grounded in lived experience. We conclude by calling for reinvigorated critical scholarship that embraces the multifaceted nature of pesticides to help find alternatives to chemically driven industrial agriculture.

The global pesticide complex and agrochemical industry

In 2008, Galt introduced the "global pesticide complex" as a concept to identify emerging patterns and dynamic interactions between pesticide production, use, regulation, and socioecological effects. The term was defined as "encompassing all aspects of pesticides' lifecycles from conception to environmental fate" (Galt 2008, p. 786). Galt centered the relationship between shifting political economies of

Table 1 Critical Social Science Research Agenda on Pesticides: Domains, Characteristics and Key Research Areas

Domain	Main Characteristics	Key Research Areas
INDUSTRY	Industry consolidation and restructuring	Corporate strategies: Generics revolution, new multinationals and relationship to legacy R&D firms; R&D and use of IPR, mergers and acquisitions and concentration, vertically integrated supply chains, outsourcing and contract manufacturing; articulations with place-based social hiearchies of difference
	Opportunities and threats of pest/weed resistance	Social and environmental implications of stacked-trait seed and chemical packages; biopesticides as accumulation frontier or alternative to chemicals
	"Safe Use" approach to end user hazards	Real world exposure on farms, in households, and farming communities; exposure in upstream production and distribution; see Knowledge of Toxicity
REGULATION	National bans	Socio-ecological afterlives: old and new "circles of poison;" hazards of chemical substitutes and their racialized burdens; policy and practice to support non-chemical alternatives
	Scalar shifts and interactions	Uneven geographies of Stockholm and Rotterdam Conventions ratifications, implementation and real-world effects; effects of regulations in major markets on other jurisdictions; motivations and outcomes of restrictions at sub-national scales
	Corporate regulatory capture	Unpack intra-state tensions (e.g., among/within Ministries of Agriculture, Health and Environment); shifts in industry-state relations over time and at different scales
	Anti-pesticide social movements	Composition, motivations, challenges, successes; motivations of farmers who mobilize against these movements
KNOWLEDGE OF TOXICITY	Multiple paradigm shifts challenging the threshold model	Situating knowledge of low-dose exposure, intergenerational effects, and more in politics of pesticide regulation; biopolitics of concern shaped by race, gender, class etc.
	Chemical cocktails	Experiences and perceptions of pesticide users and exposed communities; community epidemiology; citizen science to gauge exposure in air, water and soil
	Politics of evidence and lived experience	Biopolitics of exposure and impacts on regulation (e.g., max. residue limits); shift from proof of threshold exposure to violence via the how and why of exposure; social meaning of pesticides in particular contexts, including intimate relations among kin and community

agrochemicals and export agri-food markets, shaped by interacting dynamics between industry and regulation, and he identified new relationships that diverged from the extant understanding of the global political economy of pesticides presented in Weir and Shapiro's groundbreaking book *Circle of Poison* (1981). The circle of poison laid bare the transnational consequences of the US EPA's ban on use of organochlorine pesticides, including DDT. Following the ban, US and other global North corporations continued to produce these chemicals and export them to the global South, particularly Latin America, where their continued use harmed farmers, farmworkers, and farming communities. The "circle" was completed by the subsequent import of residue-laden foods into US and European markets, exposing northern consumers to these banned substances. Prompted by "circle of poison" concerns and a wide range of environmental and consumer movements in numerous countries, governments implemented international and national regulations on the trade of pesticides and increased monitoring of residues, with recursive effects on the pesticide complex itself.

Galt's intervention sought to account for dynamic changes emerging from relationships among a range of actors, social forces, and ecological effects. Likewise, we adopt the global pesticide complex here to shift the analytical lens beyond the farm gate, highlighting compounding interactions among agrochemical companies, agricultural science, state regulatory bodies and the science struggles that shape their decisions, environmental and social justice movements, material infrastructures, and the chemical substances themselves. We exercise caution in doing so: the "global" is not universal, encompassing, general, or placeless (Hart 2018), and those who work on and live near farms are not mere objects of disembedded forces and synthetic chemicals (Tuck 2009). Heterodox political economy along with science and technology studies are well suited to identify the relationships that materialize in and through pesticide production, on-farm use, chemical metabolism, and science and regulation, and the scales at which they do so (see Guthman 2019). In short, we offer the global pesticide complex as an analytical tool to examine connections between the spheres of production, distribution, and use that stretch unevenly across time and space; and in turn, to examine how those spheres are reshaped by the social and ecological dynamics of that unevenness.

Mapping the global pesticide industry

Contemporary global industry dynamics are commonly understood in terms of production networks that involve relations of myriad corporate actors in complicated spatial and organizational divisions of labor. Whereas industry studies tend to focus attention on transnational legacy companies such as Bayer or Syngenta, our framing of the global pesticide complex highlights the extended network of chemical production, product formulation, distribution, and use functionally coordinated among a range of firm and non-firm actors. We suggest that researchers must engage with diverse nodes of the industry to open the black box of supply chains, systematically connecting upstream developments with those further downstream to better understand what is driving industry restructuring.

The generic market revolution, in particular, has had enormous implications for the global division of labor in pesticide production and distribution. Since 1994, the value of pesticides sold worldwide has doubled to more than $60 billion today, while pesticide prices on average have dropped as a result of organizational and locational changes (IHS Markit 2020b). A first transformation concerns corporate restructuring at the global scale. A flurry of mergers and acquisitions reduced the R&D-centered transnational legacy companies to only four: Syngenta Group (comprising ChemChina-owned Syngenta and Adama, and the agricultural activities of Sinochem), Corteva, Bayer (including Monsanto), and BASF. Meanwhile, Chinese and Indian companies have become increasingly important in the sector, above all in the generic market. In 2021, twelve of the twenty largest agrochemical companies (by sales) were headquartered or were controlled by capital from China and India (IHS Markit 2021, p. 3).

Corporate restructuring in the wake of the generics revolution has resulted in an industry landscape characterized by far-flung supply chains, centering transport and logistics both as a cost and a potential source of vulnerability. An important issue here concerns evolving organizational and spatial divisions of labor between production of the active ingredient (AI) and formulation of the end-use product, in which AI is mixed with co-formulants (e.g., surfactants). R&D-centered companies increasingly turn to China and India for production, sometimes in their own factories but more often engaging in contract manufacturing relationships with a vast number of dedicated suppliers (IHS Markit, various years; S&P Global 2023). Controlling and managing these supply chains is a key challenge for the industry. Much more research is needed on corporate strategies to optimize production and distribution, for example in logistics and supply chain management or by locking farmers and service contractors into proprietary seed-pesticide platforms (Bronson and Sengers 2022; Werner et al. 2022).

Methodologically, such research would ideally involve a combination of a "top-down" analysis of the industry with a "bottom-up" reconstruction of supply chains. Given the complexity of the task, this would require a collaborative, interdisciplinary effort. Top-down analysis can start with analysis of publicly available trade and use data (e.g., Shattuck et al. 2023), public online industry and market websites, and proprietary market research. The latter can come at a prohibitively high cost that may have to be shouldered by pooling financial resources. An even greater challenge is the reconstruction of supply chains and corporate strategies from the "bottom up." Such "studying up" requires an intensive, qualitative, case-study approach. To date, there has been little research tracing global supply chains upstream from pesticide distribution to formulation to AI synthesis and production. Expert interviews and industry event ethnographies provide a good overview of key dynamics (e.g. national market and production system; corporate strategies and dynamics) and also contacts for further in-depth research. "Studying up" may also include a conjunctural "following-the-substance" approach by reconstructing the commodity biographies of particular pesticides at critical historical moments (e.g. market introduction, patent expiration, regulatory decisions, introduction of competing substances etc.). Clearly, individual researchers can only tackle a limited portion of this extensive undertaking; the ideal scenario would be for such research to be part of a systematic collaborative effort. Similar to research in other fields, these contributions can yield valuable empirical insights that will eventually converge into a comprehensive body of knowledge.

Companies' strategies for capital accumulation also need to be studied for how they articulate regional and transregional forms of social stratification, including race, caste, indigeneity, gender, and class (Hall 1980; Williams and Porter 2022). These place-based articulations of intersectional social inequality are bound up in every step of the pesticide supply chain. The global pesticide complex must be considered through the lens of specific social hierarchies and the historical and extra-local dynamics (for example, of agricultural credit and domestic and foreign investment) that reproduce, deepen, and transform these hierarchies (Aga 2021; Lapegna and Kunin 2023).

In short, there is a critical need for research on the patterns of production, trade, and use of both branded and generic pesticides, the actors and relationships among them, and the rationales and imperatives driving decision-makers. At the same time, we suggest identifying vulnerabilities of supply chains and distribution channels frequently exposed at their margins. From this perspective, what appear to be long-term strategic decisions further cementing global domination by omnipotent and fully-in-control corporations may in fact be a series of short-term fixes against unwelcome interruptions of smoothly functioning pesticide markets. Social science frameworks and methods are well suited to study these disturbances and their linked social and environmental effects. The next section turns to one such disturbance: pesticide resistance.

Economy-nature dynamics: pesticide resistance

The more a chemical pesticide is used, the more likely the target organism (insect, weed, pathogen) is to develop resistance to that chemical (Gould et al. 2018). This challenge to the pesticide industry is at once longstanding and worsening. The introduction of herbicide-tolerant genetically-modified (HT-GM) seed packages, for example, created ideal conditions for weed resistance to glyphosate (Binimelis et al. 2009), the first herbicide to be packaged with HT-GM seeds. Plant selection took place over greater land areas and for longer periods of time than any other herbicide class (Heap and Duke 2018), quickly eroding glyphosate's celebrated effectiveness.

The principal response from the pesticide industry to the challenges posed by evolutionary resistance is to enlist crop science to attempt to contain these disturbances by seeking new technological fixes that still rely upon agrochemicals (Guthman 2019). This interaction creates new market opportunities for branded and generic producers to shift or expand their chemical portfolios, which then drives what entomologist Robert van den Bosch famously dubbed the "pesticide treadmill" that locks farmers into pesticide dependence (1989 [1978]). For example, in the case of herbicides, firms now combine older, more acutely toxic chemicals such as 2,4-D, atrazine, and dicamba into new "multistacked" HT-GM seed packages. Corteva and BASF recently announced a licensing deal that allows for the development of soybeans with stacked gene traits tolerant of four herbicide modes of action (Birkett 2022). As companies seek to turn challenges into opportunities, these shifts have important but poorly understood social and ecological effects for chemical industry workers, farm workers, and farming communities.

Much more social science research is needed on these multiple aspects of growing pest and weed resistance, including how agrochemical firms are responding to declining chemical effectiveness, ways crop and weed science shore up the industry, and the uneven social, economic, and ecological effects of these responses. Social science can also illuminate strategies used by farmers to "step off" the pesticide treadmill through agroecological methods (Warner 2007; Deguine et al. 2009; Watts and Williamson 2015) as well as industry efforts to capitalize on such efforts through new biologically derived inputs (Marrone 2007; Qiu 2015). In short, nature's "liveliness" coexists with the lethal effects of pesticides on non-target human and non-human organisms and in turn reshapes the pesticide complex (Argüelles and March 2021; and see the third and fourth sections).

Regulatory vulnerability

The global pesticide industry exists in a recursive relationship with national and international regulatory frameworks that restrict or promote agrochemicals. We address the regulatory landscape and novel industry-regulation interactions in greater detail in a later section. Here we point out that the pesticide industry is keenly aware of the regulatory and legal vulnerability of agrochemical markets (e.g. Stobbart 2021; Stobbart and Rana 2022). We highlight two ways that it responds to state action through supply chain and investment strategies, especially in light of the sorts of shifts in industry practice and discourse discussed above. In so doing, we call for much greater social science investigation of how pesticide restrictions reshape patterns of uneven development.

First is the shifting geography of the industry as agrochemical companies respond to pesticide regulation, along with fiscal and trade policies, when deciding where to synthesize and formulate their products and where to locate new investments. Official, sanctioned trade is just one way that highly hazardous chemicals enter markets; they also may be produced within a country through joint ventures, subsidiaries, or state-owned companies. Foreign direct investment, for example, may be driven by the need to acquire a domestic firm with pesticide registrations in a country where legacy registrations are maintained and new ones are hard to obtain (Castro-Vargas and Werner 2022). And while many of the "lead firms" are multinationals headquartered in the global North, a growing number are headquartered in emerging economies, particularly China (e.g., Red Sun, Rainbow) and India (e.g., UPL). In addition to these legal routes, distributors also may respond to official bans by engaging in illicit pesticide trade, some of which may include products that are purposefully mislabeled.

Second, regulatory costs also condition industry investments in innovation, for example in genetic modification of seeds or, increasingly, biological pesticides (Clapp 2021; Shattuck 2021a). The cost to commercialize a new AI has increased to more than US$250 billion (Phillips McDougall 2016), in large part due to data requirements of EU regulatory agencies. Rising R&D costs have driven industry consolidation, and can help explain some of the shifts identified in the previous section. For example, with the spread of novel gene editing techniques such as CRISPR, costs of GM seed development have decreased, especially relative to those of novel pesticide chemistries. Investing in multi-stacked seeds and biological pesticides are not only responses to declining effectiveness but also may reflect a more permissive regulatory environment.

Chemical safety and real-world use

The paradox of pesticides is that their proponents must assure the world of their safety even as they are used for their ability to harm living organisms. Indeed, agriculture has served as a sink for the petrochemical industry's toxic wastes since the 19th century (Romero 2022). A recent systematic review of research on unintentional acute pesticide poisoning estimated that 385 million cases occur annually world-wide, including around 11,000 fatalities, and projected that globally as many as 44% of farmers experienced some form of pesticide poisoning every year (Boedeker et al. 2020). Acute poisonings only scratch the surface of pesticides' effects, however. Pesticides transform social and environmental relationships in complex ways that cannot be replicated in a laboratory, or conveyed by a list of AIs and their toxicological outcomes. More deeply, pesticides can and should be understood as relationships that can only be fully apprehended through attention to embodied experience, and the ways that inequality and structural violence (often through processes that extend far beyond the site of application or exposure) mediate these experiences. In the fourth section we address a host of issues around toxicity and the politics of knowledge. Here we attend specifically to the question of how pesticides are used in real-world situations and how that differs from the modes of use described by companies.

Decades of research on so-called "safe use" education, the primary form of risk management promoted by the agrochemical industry, found that knowledge and use of personal protective equipment does not prevent low-level exposures because real-world use does not match the presumed ideal (Tomenson and Matthews 2009; Shattuck 2021b). Industry representatives often use an ideal-world scenario of the rational, educated pesticide user to shift responsibility – and blame – to farmers and farmworkers (Galt 2013). Critical social scientists are well-positioned to challenge the ways real-world use is treated as an artifact of poor decisions made by poor farmers (Ríos-González et al. 2013; Stein and Luna 2021). Research is needed on ways pesticide companies, distributors, and private extension services influence the conditions of pesticide application, for example through market capture or a hands-off approach to after-sale use. This requires sensitivity to the highly uneven distribution of risk. Ethnic minorities, workers racialized as "non-white", migrants, and other marginalized workers are often more likely to do the work of pesticide application (e.g., Schwartz et al. 2015). While large agribusinesses tend to hire more men to apply pesticides, women and children largely undertake care work – such as washing pesticide-laden clothes and containers – that exposes them in invisibilized ways. Thus, understanding the effects of pesticide exposure demands attention to the lived and differentiated experiences of agricultural labor, households, and communities (Wright 1990; Mera-Orcés 2001; Schwartz et al. 2015; Stein and Luna 2021).

A related knowledge gap concerns chemical hazards for those who labor in pesticide synthesis and formulation and the communities where these plants are sited, aspects often overlooked in a literature that focuses mainly on agrarian livelihood impacts and consumption. Synthesis and formulation of agrochemicals expose industrial workers and their communities to toxic chemical substances across the supply chain. Pesticide production, transport, and storage led to some of the most devastating industrial accidents of the late 20th century, including the ICMESA toxic cloud release in Seveso, Italy, in 1976, the Union Carbide methyl isocyanate gas leak in Bhopal, India, in 1984, and the Sandoz agrochemical warehouse leak into the Rhine in Switzerland in 1986 (Bertomeu-Sánchez 2019). These tragedies mobilized environmental movements and motivated new regulations. There is evidence of recent accidents at pesticide production plants in China (e.g., Cao et al. 2018; He et al. 2014), but less is known about these events or any regulatory actions in their wake.

Tracing a dynamic regulatory environment

The suite of recent changes described above (including new supply chain geographies, the shift to generics, and related harms for workers and communities) come on the heels of decades of regulation, the outcomes of which themselves dynamically reshape the global pesticide complex. In the decades following Rachel Carson's *Silent Spring* (1962), environmental movements successfully pressured governments to introduce regulations protecting human and ecological health from pesticide exposures in manufacturing, application, and food consumption. Scholars and activists would soon expose the limits of these national-scale regulations in the context of a global agri-food system, most notably in *Circle of Poison* (Weir and Shapiro 1981). As described above, the book traced both pesticide flows and the regulatory loopholes that reflected and reinforced the world's neo-colonial and post-colonial divides. International development agencies began promoting pesticide use globally in the late 1950s without a standard set of regulatory guidelines or frameworks for their use (Jansen and Dubois 2014). Growing awareness of the transnational dimension of pesticides led to the formation of the Pesticide Action Network (PAN) in 1982, legislation in numerous countries restricting exports or imports, and a UN resolution on notification of hazardous exports.

Civil society organizations campaigned for the rest of the century to achieve binding, multilateral regulations on pesticide use and trade. As agrochemical firms increased their exports of substances now banned in the US and Western Europe, PAN, Oxfam, and other groups advocated for inclusion of a Prior Informed Consent (PIC) process in transnational frameworks whereby exporters would share information on hazardous pesticides with importers. FAO and UNEP incorporated PIC procedures into voluntary codes, and EU member states implemented a separate, binding procedure (Jansen and Dubois 2014). Overcoming industry opposition, the Rotterdam Convention (which came into force in 2004) requires exporters to inform importing nations of existing bans or restrictions on PIC-listed chemicals, which importing countries can then refuse (Jansen and Dubois 2014). Civil society advocacy eventually yielded a process to ban the trade of some hazardous substances altogether. Coming into force the same year as Rotterdam, the Stockholm Convention prohibits trade of some persistent organic pollutants (POPs), including sixteen pesticides by 2022.

The Rotterdam and Stockholm Conventions are the outcomes of tremendous struggles by diverse, transnational coalitions of civil society groups and some allies in government in the face of fierce opposition from the pesticide industry and its government supporters. If social science has paid modest attention to the conditions that led to these and other pesticide regulations, even less research has been done on their "afterlives," or what happens in the wake of their adoption. As with the pesticide industry, however, information about regulation is similarly dispersed and patchy; innovative methods are needed to gather, share, and represent information on the regulatory landscape.

The afterlives of pesticide bans

We call for systematic attention to the socio-ecological afterlives of pesticide bans, or the outcomes and unintended consequences of pesticide restrictions that re-shape the pesticide complex and the social and spatial hierarchies of exposure and risk at its heart. Key questions are about how chemical companies, farms large and small, regulators, activists, and others respond to restrictions and especially to bans, and bans' myriad effects and variation over space and time. Research should elucidate how restrictions and bans have been implemented in ratifying countries: to what degree and under what social, political, and economic conditions these rules are implemented. Research should also address the effects for non-ratifying countries, as well as what happens if civil society groups are less mobilized around pesticide issues over time. Concerns such as these raise broader questions about what "bans" and "restrictions" really are, both theoretically and empirically.

One key concern centers on what replaces a chemical if it is restricted or banned, especially if non-chemical alternatives to pest control are not directly promoted. DDT and other organochlorine pesticides offer salient examples. In the US Mississippi delta region, plantation owners secured exemptions for the continued usage of DDT after early restrictions and the 1972 national ban; the political power of plantation interests was based on the racialized disenfranchisement of Black southerners (many of whom were smallholding farmers and farmworkers) (Woods 2017; Williams 2018). Moreover, the use of acutely toxic organophosphates and other organochlorine insecticides, which already had been increasing as insects evolved resistance to DDT, rose further as the DDT ban was fully implemented (Wright 1990; Davis 2014). In the 1980s, Wright found similar dynamics in Mexico as farmers switched from banned organochlorines to lower-residue organophosphate and carbamate insecticides like parathion and aldicarb to avoid US export shipments being rejected for illegal residues (Wright 1986). Contrary to the earlier "circle of poison" thesis, few of these highly toxic substances were imported from the US, but were produced in Mexico under import-substitution policies. As on cotton plantations in the Mississippi delta, the switch from organochlorines to organophosphates put Mexican farmworkers at much greater risk since these insecticides are more acutely toxic; indeed, many would eventually also be banned in over 125 countries (PAN 2022) and included in the Rotterdam Convention.

In short, concern for the collateral effects or unintended consequences of national bans has since grown to include the fundamental question of what replaces banned substances, and how the burden of adapting to bans is distributed. At the global level, civil society movements have sought to prevent a pattern of chemical input-substitution (e.g., Watts and Williamson 2015). They have successfully introduced language, for example in the Stockholm Convention, on the need to support countries in replacing listed chemicals not with another chemical but with "ecosystem-based alternatives". Policymakers have often approached the question of pesticide use from an individual decision-making perspective. Yet, the complexity of pesticide use – especially in the context of bans and restrictions -- calls for a more relational perspective that can grasp different agencies, both human and non-human (Guthman 2019; Müller 2021; see also Robbins 2007). Farmers' ability to shift to sustainable pest management methods depends upon social investments in training and appropriate technology, farmer income support during transition times, and changes in input supply channels and consumer expectations. Research is needed to figure out how bans work in practice and over time, and to untangle how farmers successfully reduce their pesticide use in their wake.

Scales, patterns, and connections across regulatory jurisdictions

A key need is for research on interactions across different jurisdictions and at different scales. Not only are there explicitly international efforts like the Rotterdam and Stockholm conventions, but the regulatory standards of the EU's European Food and Safety Administration and the US Environmental Protection Agency have implications well beyond their borders. For one, their regulatory frameworks are sometimes adopted by other countries. The agrochemical industry in Costa Rica, for example, has sought to ease registration requirements by authorizing pesticides already registered in a "reference country" such as the US for use in Costa Rica, effectively displacing this state regulatory function (Castro-Vargas and Werner 2022). In addition, restrictions such as the EU's maximum residue limits (MRLs) on imports aim to protect consumers but leave farmers, farmworkers, and communities vulnerable, especially in global South domestic markets. Existing research shows that when exporting countries' pesticide regulations and/or their enforcement are weak, there is more intensive pesticide use for domestic consumption and less intensive use for exports (Arbona 1998; Williamson 2003; Barling and Lang 2005; Galt 2009, 2014; Barri and Wahren 2013).

At the same time, citizens' concern about weak or absent protections—including in the US and Europe—is precipitating not only alternative food movements (e.g., organics) but also a large number of campaigns for regulations to be enacted at other scales, including by municipalities and states or provinces. Such sub-national restrictions have been enacted not only in the US and across Europe, but also in countries of the global South such as Argentina (Palmisano 2018; Arancibia and Motta 2019; Schmidt et al. 2022). Much remains unknown about this shift to local-level regulation, including its extent and effectiveness, barriers (e.g., state preemption), who and what are actually protected, the political ramifications, and wider repercussions for communities most harmed by pesticide exposure.

In an era of supply chain capitalism, the geography of pesticide production is also shaped by knock-on effects of regulations in places that concentrate upstream activities. When China implemented new "blue sky" policies, for example, to regulate its highly polluting pesticide manufacturing sector, the resulting reorganization and increase in agrochemical prices created opportunities for new generic producers in India operating under more permissive conditions (Zhang et al. 2011; Chow 2018; Oliveira et al. 2020). More recently, in 2021, China's cap on industrial energy consumption in Yunnan province put a halt to energy-intensive mining for yellow phosphorus for production of glyphosate. Combined with supply shocks from declining US glyphosate production after flooding along the Gulf Coast, prices of generic glyphosate tripled over the course of 2021 and early 2022 (Li 2022). Lawsuits can also shape supply chain geography, for example as Bayer responds to its spectacular losses in the US courts over glyphosate by moving to end sales of Roundup in the US household market, while maintaining the agricultural market (Hals et al. 2021).

Corporate capture of national and global regulation

Restrictions on pesticides, however, are just one dimension of state regulation. Indeed, states often focus policy and resources towards pesticide promotion among farmers and protection of the agrochemical industry. State support of pesticides was central to the Green Revolution and related development projects beginning in the 1940s. Couched in terms of states' commitments to food self-sufficiency while offering technological fixes to defer peasant movement demands for comprehensive land redistribution, the publicly funded Green Revolution also paved the way for developing countries' future consumption of agrochemical inputs (Cullather 2010; McMichael 2013; Patel 2013). After the 1980s debt crisis, many states were forced into neoliberal reforms, which included cutting agricultural subsidies and extension services. Corporate actors filled the gap. Companies supplied seed and pesticide packages to farmers under contract, while state extension agents were replaced by pesticide vendors. Emblematic is the so-called "new Green Revolution for Africa," promoted by multinational corporations and philanthropic capital, particularly the Bill and Melinda Gates Foundation (Moseley et al. 2017; Boafo and Lyons 2022). A key research need is to study the role of these regulatory shifts on the pesticide complex, including the ability of the chemical industry to capture the regulatory process at multiple scales, not least through the "revolving door" between industry and regulatory agencies (Meghani and Kuzma 2011).

At the same time, regulatory capture itself must be unpacked. As Jansen notes, "while the claim that the industry attempts to influence the regulatory process may well stand, this does not explain why regulatory regimes take the particular shape that they do" (2008, p. 576). Neither the state nor capital are uniform actors; for example, Ministries of Environment, Health, and Agriculture are often at loggerheads over pesticide regulations (e.g., Hetherington 2020), while firms and farmers' associations may be divided by competitive pressures and broader political loyalties. Moreover, competition between R&D multinationals and largely domestic generic sectors historically played out in contests over requirements for pesticide registration (Jansen 2017). But industry restructuring, including growth of generic sectors in middle-income countries, and a dearth of patented new chemicals are contributing to efforts to loosen requirements for registration of generic substances in places such as Colombia (Valbuena et al. 2021), Brazil (Oliveira et al. 2020) and Costa Rica (Castro-Vargas and Werner 2022).

In this context, there are multiple areas for fruitful research on state-industry relations, including on the scope of such relations both within countries and in international agencies such as the UN FAO. A 2020 Letter of Intent signed between the FAO and the leading pesticide industry group, CropLife International, has caused much concern among civil society groups over regulatory capture at the UN agency. An open question is how and why there are shifts in these relations over time, such that regulatory bodies become more or less collaborative with industry. More needs to be known about how networks of structural privilege and cultural capital influence strictness of enforcement. There are also questions about who bears the burden of deregulatory approaches, i.e., when responsibilities for protecting health and environment are turned over to individual workers, farmers, communities, and consumers. Comparative, cross-country work would be very helpful here.

Social movements and struggles over social reproduction

Regulatory regimes are shaped by civil society broadly defined. Whether the state prioritizes concerns for safety and health — and for whom — is largely determined by the ebb and flow of social movements and organizations that make such demands and marshal coalitions to support them (e.g., Barri 2010; Schurman and Munro 2010; Arancibia and Motta 2019). For example, PAN (introduced above for its work on the Rotterdam Convention) brings together scientists, farmers, and other stakeholders in its various regional networks to follow pesticide regulation over time (including its definitive list of national bans, PAN 2022), contest regulatory capture, and demand reforms in the face of regulatory failures. However, less is known about the specific politics these diverse movements articulate, how grounded these campaigns are in concerns of chemical workers or farming communities versus consumers, and how local campaigns reverberate in other locations, shaping regulations elsewhere.

Anti-pesticide movements are part of diverse struggles against alienation and dispossession. Often, they form part of larger environmental and environmental justice, livelihood, and health movements. For example, smallholders and peasants reclaim their land and their livelihoods, struggling over re-production, advancing non-market coordination and value regimes over market ones, and demanding a fairer share of profits from market relations (Barri and Wahren 2013; Lapegna 2016). Industrial workers in the agrochemical industry also fight for a fairer share of the profits and rents accumulated through supply chains. Residents and workers whose health is seriously affected by pesticide exposure wage successful public campaigns against Monsanto and other global players (e.g., Arancibia and Motta 2019). Many agricultural producers, especially family operations, are critical of the chemical treadmill on which they find themselves (Galt 2014). In many cases, mid-size farmers may not see viable alternatives to pesticide-dependent agriculture, and they can be ambiguous about pesticide use and exposure (Lapegna and Kunin 2023). A key response by pro-capital representatives in the global North is to marginalize and delegitimize unwelcome contestation. Such othering regularly involves representations of a backward, unreliable global South: in the shape of the wayward (Chinese) generic producer, the irresponsible state that is unwilling to regulate, the uneducated unruly farmer or peasant who applies otherwise safe pesticides wrongly, or agents engaged in criminal activities (e.g., pesticide smuggling).

Research is needed, therefore, to understand the landscape of anti-pesticide social movements and their goals, motivations, and challenges, as well as how some farmers may also mobilize against regulations and in support of conventional agriculture (van der Ploeg 2020; Müller 2021). Key questions remain as to the consequences of such social movements. Seen through the lens of the global pesticide complex, this includes not only the extent of their success, but also how such challenges shape the terms of engagement for farmers, communities, pesticide companies, and others, which are, in turn, remade by these contests.

Integrative approaches to toxicity and the politics of knowledge

There has been an enormous paradigm shift in scientific knowledge since the 2000s as scientists learn more about the mechanisms through which chemicals act biologically, such as endocrine disruption, epigenetics, and alteration of the microbiome. This new scientific paradigm, which shows more intricate links between exposure and harm than previously assumed, also faces organized campaigns of denial, particularly in efforts to undermine regulation (Mansfield 2021). In this context, an important role for social scientists is to collaborate with other scientists to improve the body of knowledge, for example regarding how the industry's restructuring discussed above might alter the landscape of sociospatial health disparities or socioecological dynamics, such as implications for pollinators (Sponsler et al. 2019).

While it might seem that scientific findings should be able to resolve debates about activist "fearmongering" vs. corporate "deceit", such questions cannot be entirely resolved by science because they are also fundamentally questions about scientific authority and expertise, what counts as evidence, and which actors have the power to shape policy. A robust literature from science studies, sociology, and geography on a range of chemical substances has changed the way social scientists approach the question of toxicity (Murphy 2006; Vogel 2013; Shapiro 2015; Cordner 2016; Liboiron 2021). Not only have these fields begun to "open the black box of the body" – to see bodies and environments as radically porous extensions of one another (Guthman and Mansfield 2013) – but a growing chorus of scholars has also emphasized the need to see the chemical itself as relational: its materiality and modes of action are shaped by its existence in mixtures, ecosystems, bodies, and complex socio-natures (Romero et al. 2017). Rethinking pesticides along these lines alters our understanding of toxicity and evidence by emphasizing lived experiences of pesticides in everyday life. Toxicity, as a social and environmental process of harm, is defined by the highly context-dependent social structures that shape the use and effects of particular compounds (Liboiron et al. 2018). Multiscalar structural forces of racism, colonialism, and geographically uneven development shape the variegated toxicities, harms, and benefits of pesticides.

Paradigms of toxicity and the role of science

Because the struggle to define chemical safety has been ongoing for more than a century (Whorton 1974), research is needed on the paradigms of toxicity that underpin present day regulatory frameworks. The EU follows a hazard-based model for chemicals regulation, which focuses on the potential of a chemical to cause harm. In sharp contrast, nearly all other countries, including the US, adopt a risk-based approach that requires evidence of both hazard *and* exposure (Vogel 2013; Cordner 2016; Liboiron 2021). Both frameworks reflect the broader epistemology of modern chemical regulations, which reduce complex toxic environments to assessments of molecule-by-molecule evidence of harm (Hepler-Smith 2019). Furthermore, the traditional focus is on acute toxicity, cancer, and teratogenesis, and the foundational assumption is that there is some threshold below which a chemical exposure is safe, i.e., "the dose makes the poison." Institutions such as the US EPA still rely heavily on this threshold model of harm, which gives a right to pollute as long as exposures stay below that purported threshold.

Over the past several decades, the avalanche of paradigm-shifting studies in toxicology, epidemiology, epigenetics, microbiomics, and so forth have demonstrated the fallacy of this fundamental tenet. For many chemicals there is either no threshold of safety or there are *greater* effects at lower levels; this is especially true for endocrine-disrupting chemicals. New generation pesticides, many of which are not acutely toxic, may nonetheless have genotoxic, carcinogenic, endocrine disrupting, or other deleterious effects which can be difficult to determine with certainty over a biologically and politically relevant timeframe (Mesnage et al. 2017; Mostafalou and Abdollahi 2017). Non-threshold pollutants are now part of the fabric of life and produce harms that are often illegible to scientists and regulators in both the short and long term.

One fundamental challenge to the dominant paradigm of toxicity is the potential time lags between exposure and negative effects. Many chemicals, including many pesticides, cause an array of health problems over the lifespan and even intergenerationally, making pesticide exposure a reproductive justice issue. One example is DDT, which continues to be used for vector control in some areas of Asia, Latin America, and Africa. Despite concern based on animal studies, it was not known to cause cancer in humans until 2015 when a case-control study found that women whose mothers were exposed to DDT while pregnant in the 1960s were four times more likely to develop breast cancer (Cohn et al. 2015).

The volatile combination of new paradigms and new compounds leads not only to expected scientific uncertainty, but also to widespread debates about good science and the forms of evidence that should be considered in regulatory decision-making (Mansfield 2021). Glyphosate is a good example. Claims of the compound's safety, meaning lack of acute toxicity, drove increasing use, including as pre-harvest and post-harvest crop treatments (Werner et al. 2022). To facilitate these uses, US regulators have repeatedly increased tolerance levels of allowed residues on food and animal feed, by as much as 2,000-fold (Benbrook 2016). Whereas the World Health Organization has declared that glyphosate is probably carcinogenic to humans, the US disputes this conclusion. These differences are based on claims about what counts as "good science," including reliance on evidence from proprietary versus public sources, inclusion of co-formulants in assays, and the definition of exposure itself (i.e., dietary versus occupational) (Benbrook 2019).

Different paradigms of toxicity and regulation put the onus of proof on different groups of people. A hazard-based approach puts a greater burden of proof on manufacturers of agrochemicals to prove their products are safe; a risk-based approach puts more burden on under-resourced rural workers, socio-environmental organizations, and the scientific community to prove harm. Both models involve unequal social costs. Social scientific research is necessary to understand the logics of regulatory science and the conditions under which different logics are embraced and contested during regulatory processes (Harrison 2011). More research is needed on what actually happens in influential agencies such as the EPA and WHO, as well as on how knowledge of low-dose exposure, intergenerational effects, and so forth are situated in these politics of pesticide regulation. Also needed is a better understanding of the ongoing biopolitics of pesticides and their regulation, including the effects about which people are most concerned and the gender, race, ethnicity, ability, and age dynamics of these concerns.

Industry restructuring, cocktails of chemicals, and regulatory uncertainty

A key concern for health and environmental wellbeing is the proliferation of new formulations of pesticides with broadly illegible effects as of yet. The proliferation of these formulations, in which an active ingredient is mixed with different combinations of "inert" ingredients, is driven by several factors discussed above: the rise of the generics sector, pests' growing resistance to existing pesticides, and the lack of innovation of new AIs. Developing new formulations using mixes of AIs is one way to try to address the problem of resistance.

Formulations of pesticides are rarely subjected to environmental and health evaluation, which instead focuses on a single AI. The environmental, social, and health effects of chemical cocktails and transnational implications for the pesticide complex are all open questions. Co-formulants can include harmful surfactants such as fluorinated chemicals (PFAS) (known as "forever chemicals" because they do not break down in the environment), which are associated with a wide range of health and developmental problems (Fenton et al. 2021). Moreover, different combinations of surfactants, adjuvants, and active ingredients can be more toxic than individual ingredients alone. The few studies on cocktail effects – of either combinations of active ingredients or their formulations – show synergistic damage (e.g., Jaeger et al. 1999; Nørgaard and Cedergreen 2010; Lukowicz et al. 2018). A research challenge is that data on the products being used in agriculture are often missing, and even if such information is available, surfactants and adjuvants are often marked as "trade secrets" and thus not listed in pesticide ingredients. This can make it nearly impossible to trace harmful exposures or even estimate the scale of potentially serious problems.

In this context, research is needed on how workers, farmers, and communities confront this changing landscape of pesticides. Because long term cohort studies, the gold standard in epidemiology, are almost impossible to conduct in most of the world, social scientific approaches that document the experiences and perceptions of pesticide users provide crucial insight that is missed otherwise. How do people who variably "work with, transform or accidentally ingest" (Richardson and Weszkalnys 2014) pesticides at different nodes of supply chains experience agrochemical exposure and how do they make themselves heard? This requires a mixed methods approach and can benefit from collaborations between biophysical and social scientists. For example, community or popular epidemiology, a method that relies on household surveys and examines the socio-environmental and economic situation of the affected population as well as their working and living conditions, is an important tool to understand realities of pesticide exposure among different social groups (Tognoni 1997; Breilh et al. 2005). Where aerial application of pesticides is broadly used by farmers and plantation managers, people living and working nearby bear the burden of increasing pesticide exposure, often with unknown and understudied long-term effects (Domínguez and Sabatino 2010). Citizen science initiatives to "catch" pesticide drift can make the cocktail of exposures in farmworker communities legible (Marquez et al. 2020). Interviews with rural workers can illuminate what chemicals are being used, how, and in what combinations, and low-cost screening tests in the field can indicate how widespread exposures may be (Shattuck 2021b). These approaches can be especially effective if combined with environmental monitoring of water and soil contamination. Studies involving community partnerships can also elucidate how toxicity is experienced differently based on gender, race, and social marginalization, and what populations have been deemed worth "sacrificing" in the name of agricultural production and why.

Politics of evidence

As the standard paradigm of toxicity erodes, chemical corporations—and those aligned with them—have responded with a strong defense of pesticides' safety and necessity for addressing global food security. To do so, they have conducted their own studies on the safety of individual chemicals, informally and formally influencing what counts as "good science" (e.g., Jansen 2008; Benbrook 2019). Residue standards, for example, illustrate how scientific principles can hide political decisions about who and what counts. International maximum residue limits are established by the Joint FAO/WHO Meeting on Pesticide Residues based on "average daily intake," a method subject to much criticism because it focuses regulatory attention on consumption but fails to account for bioaccumulation, occupational and community exposure, and variations in body size (Wargo 1998; Johnson 2018).

Pesticide workers and other exposed community members across the world are structurally disadvantaged vis-a-vis industrial farming and agrochemical companies, and very often lack the scientific and legal literacy to make their evidence legible within narrow regulatory metrics. When evidence does exist, this might pertain only to a certain population (Navas 2022). Even if it is possible to isolate a discrete pesticide compound in the body, it may have non-discrete effects because of a range of other life conditions (Liboiron 2021). For example, prior exposures can condition the effects of subsequent exposures (Nash 2008) and long-term effects of pesticide use are confounded by lack of access to health care, poor health surveillance, and the general health stressors that come with being poor and rural (Shattuck 2021b). Thus, while it is difficult if not impossible to trace harm directly from exposure, it is no stretch to imagine that the ubiquity of exposure represents large-scale slow violence (Nixon 2011). Questions of minimum thresholds will always be uncertain; asking instead about violence — about the "how and why" of such widespread and shifting exposures, and the very real fears and uncertainties they generate — shifts attention from individualized outcomes to wider sets of relations at politically relevant scales (Liboiron 2021).

In sum, innovative research is needed on the epistemology of toxicants: to understand both what chemicals do (as molecules, mixtures, and agents in biological organisms and landscapes) and the politics of how we come to know them. Research is needed on how the matter of the chemical comes to matter, and how that changes as it moves along the commodity chain, through circuits of capital, in and out of different social relations, and informed by situated cultural understandings of risks and harms.

Lived experience

How agrochemicals intersect with agrarian change and with social lives, identities, race, and gender is not predictable. It does not lend itself to easy normative claims in the immediate term, especially as it also means that those most affected might be resistant to making change (Stein and Luna 2021; Senanayake 2022). Increasing pest pressure, market liberalization, promotion of agrochemicals, poorly functioning extension systems and lack of public spending on alternatives can leave smallholders little choice but to rely on agrichemicals (Andersson and Isgren 2021; Aga 2019). Economic pressures, labor shortages, and cultural change can intersect to intensify the pesticide treadmill (Luna 2020). All this implies that agrarian conditions matter, as does the broader social life of agrochemicals.

As we have alluded, the burgeoning social science interest in the epistemology of toxicity and pesticide science is also raising key questions about how pesticides are experienced. Studies have shown, for instance, that there is a gendered perception of the risks of pesticide exposure (e.g., Mera-Orcés 2001; Evia Bertullo 2018; Kunin and Lucero 2020), and that local cultures and social class shape the subjectivities of pesticide users (e.g., Galt 2013). The role of lived experience, and variation across experiences, is central to the politics of evidence regarding pesticides' harms.

Highlighting experience also means recognizing that these compounds support various kinds of livelihoods: they are part of the fabric of life for many people, which helps explain pesticides' ubiquity. Pesticides are entangled in discourses of race, caste, and modernity (Luna 2018; Aga 2019; Williams 2021). They can be experienced as a vector for prosperity and progress (Lapegna and Kunin 2023) or as a way of achieving greater social status (Aga 2019; Choudhury and Aga 2019). Agrochemicals can allow women to manage farms alone while their partners migrate for work (Hu and Rahman 2016). As rural wage rates have risen across much of the world, herbicides especially have also become an economic necessity (Haggblade et al. 2017). And economically enabling effects of agrochemicals can positively alter social determinants of health in the immediate term even as their likelihood to undermine long-term health is widely recognized by users.

The effects of pesticides are highly differentiated even at the local scale. The same chemical compound that represents profitability for a large farm owner can simultaneously mean sickness or even death for farm workers, and extend ecological destruction and environmental dispossession to neighboring and downstream communities. In the Colombian Caribbean, for example, glyphosate usage extends colonial dispossession, and the harms of glyphosate are mediated by and intertwined with gendered and racial violence (Berman-Arévalo and Ojeda 2020). The gendered, and often patriarchal, dynamics of agrarian production and rural land access can condition and differentially situate the effects and experiences of chemicals in ways that resist easy universal claims.

We need more social scientific and humanistic understanding of the material tangibility of individual chemicals and the varied work they do in the world. We also need more understanding of the social meanings of pesticides (and their harms) in different contexts, including in intimate social relationships, such as among kin and community (Kunin and Lucero 2020; Leguizamón 2020).

Conclusion: engaging with pesticides as multifaceted research objects

A new critical social science research agenda must account for pesticides as multifaceted research objects: as central pillars for the present practice of conventional agriculture, sources of pollution and harm, tools of violence, opportunities to lower burdens of farm work and accumulate rural capital, biocides that harness and erode susceptibility, barriers towards more sustainable farming futures, and more. The agenda outlined above highlights the need for innovations that identify and unpack the recursive, interacting relationships between a dynamic, changing agrochemical industry, regulatory actions shaped by societal struggles over the environment and human health, and shifting paradigms of toxicity. This is what we mean by the global pesticide complex as a heuristic: the agenda we have laid out seeks to parse relationships and interactions within and across these domains of industry, regulation, and knowledge of toxicity. Such an approach can enable researchers to identify the evolving inequalities of today's chemical geographies and to support efforts to find alternatives to chemically driven industrial agriculture.

Research with communities on pesticides must avoid what indigenous studies scholar Eve Tuck calls "damage-centered research" (2009). A damage-centered approach defines these communities singularly through their chemical exposures and harms; it reflects a theory of change that, like litigation, rests upon proving damage to advocate for remedies. But this reductionist approach fails to account for the multifaceted nature of pesticides themselves, the environments in which they act, or the people who produce, use, and otherwise come into contact with them. A "desire-based" research framework (Tuck 2009) instead embraces complex and conflicting relationships between pesticide production and use, farming, livelihood aspirations, health, and the environment and understands that navigating these relationships is a long-term process. It also eschews a tendency to train our social science lens too keenly on agro-ecological alternatives: while these are important initiatives, their limits and possibilities must be understood within a context of rapidly expanding pesticide use.

Finally, there is tremendous scope to reinvigorate collaborations within and among the social sciences, across the social and biophysical sciences, and between scholars and civil society organizations. Given the widespread problem of data availability and reliability, collaborations are necessary to offer a more comprehensive picture. Pesticide research builds upon a rich tradition of science-civil society collaboration. As we have discussed here, those collaborations and their pivotal role in the development of the Stockholm and Rotterdam conventions occurred during a period when pesticide production was dominated by European and North American firms. The implications of the agrochemical industries' supply chain restructuring and the rise of generics for these conventions and other forms of regulation must be fleshed out — indeed, the need is urgent. Collaborative research can also aid in moving novel toxicity paradigms from the research margins to the centers of pesticide regulatory implementation. Such collective research efforts coordinated between social scientists and biophysical and health scientists might have greater power in these regulatory settings. We offer this research agenda, written by a mix of social scientists from different disciplines and parts of the world, along with civil society-based and academic biophysical scientists, as a step forward in these directions.

Acknowledgements This paper emerged from a workshop in November 2021 called Global Glyphosate: New Challenges in Regulating Pervasive Chemicals in the Anthropocene. We are grateful to the University at Buffalo's Baldy Center for Law and Social Policy and the Community for Global Health Equity for supporting the workshop. Research was supported by US National Science Foundation (Grant #BCS2026088 - The Generic Herbicide Industry) and Swiss National Science Foundation (Grant #204766 - Making Herbicide Markets). We are grateful to Caitlyn Sears and Gizem Orgev for research support and to Aniket Aga and Simone Müller for comments on earlier drafts.

Funding Open access funding provided by University of Zurich.

References

Aga, A. 2019. The marketing of corporate agrichemicals in western India: theorizing graded informality. *The Journal of Peasant Studies* 46(7): 1458–1476. https://doi.org/10.1080/03066150.2018.1534833.

Aga, A. 2021. *Genetically modified democracy: transgenic crops in contemporary India*. New Haven: Yale University Press.

Alavanja, M. C. R. 2009. Pesticides use and exposure, extensive worldwide. *Reviews on Environmental Health* 24(4): 303–309. https://doi.org/10.1515/REVEH.2009.24.4.303.

Andersson, E., and E. Isgren. 2021. Gambling in the garden: Pesticide use and risk exposure in Ugandan smallholder farming. *Journal of Rural Studies* 82: 72–86. https://doi.org/10.1016/j.jrurstud.2021.01.013.

Arancibia, F., and R. Motta. 2019. Undone science and counter-expertise: fighting for justice in an argentine community contaminated by pesticides. *Science as Culture* 28(3): 277–302. https://doi.org/10.1080/09505431.2018.1533936.

Arbona, S. I. 1998. Commercial agriculture and agrochemicals in Almolonga, Guatemala. *Geographical Review* 88(1): 47–63. https://doi.org/10.1111/j.1931-0846.1998.tb00095.x.

Argüelles, L., and H. March. 2021. Weeds in action: vegetal political ecology of unwanted plants. *Progress in Human Geography* 46(1): 44–66. https://doi.org/10.1177/03091325211054966.

Barling, D., and T. Lang. 2005. Trading on health: Cross-continental production and consumption tensions and the governance of international food standards. In *Cross-continental agro-food chains*, ed. N. Fold and B. Pritchard, 1st Edition, 39–51. London and New York: Routledge.

Barri, F. R. 2010. Pueblos fumigados en Argentina: resistencia epidemiológica comunitaria al modelo económico de los agronegocios. *Ecología Política* 40: 67–72.

Barri, F., and J. Wahren. 2013. El modelo del 'agronegocio' en la Argentina: El paradigma cientificista-tecnológico. In *Actividades extractivas en expansión: ¿Reprimarización de la economía Argentina?*, eds. N. Giarracca, and M. Teubal. 73–96. Buenos Aires: Antropofagia.

Benbrook, C. M. 2016. Trends in glyphosate herbicide use in the United States and globally. *Environmental Sciences Europe* 28(3)https://doi.org/10.1186/s12302-016-0070-0.

Benbrook, C. 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). https://doi.org/10.1186/s12302-018-0184-7.

Berman-Arévalo, E., D. Ojeda. 2020. "Ordinary geographies: Care, violence, and agrarian extractivism in 'post-conflict' Colombia. *Antipode* 52(6): 1583–1602. https://doi.org/10.1111/anti.12667.

Bernhardt, E. S., E. J. Rosi, and M. O. Gessner. 2017. Synthetic chemicals as agents of global change. *Frontiers in Ecology and the Environment* 15(2): 84–90. https://doi.org/10.1002/fee.1450.

Bertomeu-Sánchez, J. R. 2019. Introduction: pesticides: past and present. *HoST - Journal of History of Science and Technology* 13(1): 1–27. https://doi.org/10.2478/host-2019-0001.

Binimelis, R., W. Pengue, and I. Monterroso. 2009. Transgenic treadmill': responses to the emergence and spread of glyphosate-resistant johnsongrass in Argentina. *Geoforum* 40(4): 623–633. https://doi.org/10.1016/j.geoforum.2009.03.009.

Birkett, R. 2022. Corteva and MS Tech ink North Am deal with BASF on Enlist E3/nem res soybeans. S&P Global Crop Science Market Reporting. 30 June 2022.

Boafo, J., and K. Lyons. 2022. The rhetoric and farmers' lived realities of the Green Revolution in Africa: case study of the Brong Ahafo region in Ghana. *Journal of Asian and African Studies* 57(3): 406–423. https://doi.org/10.1177/00219096211019063.

Boardman, R. 1986. *Pesticides in world agriculture: the politics of international regulation*. 1st ed. Houndmills, Basingstoke, Hampshire: Macmillan.

Boedeker, W., M. Watts, P. Clausing, and E. Marquez. 2020. The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review. *Bmc Public Health* 20(December): 1875. https://doi.org/10.1186/s12889-020-09939-0.

Breilh, J., A. Campaña, F. Hidalgo, D. Sánchez, M. L. Larrea, O. Felicita, and E. Valle et al. 2005. Floriculture and the health dilemma: Towards fair and ecological flower production. In *Latin American health watch: Alternative Latin American health report (2005)*, ed. Centro De Estudios y Asesoria en Salud, 70–83.

Bronson, K., and P. Sengers. 2022. Big tech meets big ag: diversifying epistemologies of data and power. *Science as Culture* 31(1): 15–28. https://doi.org/10.1080/09505431.2021.1986692.

Cao, G., L. Yang, L. Liu, Z. Ma, J. Wang, and J. Bi. 2018. Environmental incidents in China: lessons from 2006 to 2015. *Science of the Total Environment* 633(August): 1165–1172. https://doi.org/10.1016/j.scitotenv.2018.03.271.

Carson, R. L. 1962. *Silent spring*. Boston: Houghton Mifflin Company.

Castro-Vargas, M., and M. Werner. 2022. Regulation by impasse: Pesticide registration, capital and the state in Costa Rica. *Environment and Planning E: Nature and Space*, August. https://doi.org/10.1177/25148486221116742.

Choudhury, C., and A. Aga. 2019. Sowing the seeds of climate crisis in Odisha. People's archive of rural India. 2019. https://ruralindiaonline.org/en/articles/sowing-the-seeds-of-climate-crisis-in-odisha/. Accessed June 28, 2023.

Chow, T. 2018. Top 20 Indian agrochemical companies in FY 2017-18: Backward integration to secure the future. *2018 India pesticide suppliers guide*, August 2018.

Clapp, J. 2021. Explaining growing glyphosate use: the political economy of herbicide-dependent agriculture. *Global Environmental Change* 67: 102239. https://doi.org/10.1016/j.gloenvcha.2021.102239.

Cohn, B. A., M. La Merrill, N. Y. Krigbaum, G. Yeh, J.-S. Park, L. Zimmermann, and P. M. Cirillo. 2015. DDT exposure in utero and breast cancer. *The Journal of Clinical Endocrinology & Metabolism* 100(8): 2865–2872. https://doi.org/10.1210/jc.2015-1841.

Cordner, A. 2016. *Toxic safety: flame retardants, chemical controversies, and environmental health*. New York: Columbia University Press.

Cullather, N. 2010. *The hungry world: America's cold war battle against poverty in Asia*. Cambridge, Mass: Harvard University Press.

Davis, F. R. 2014. *Banned: a history of pesticides and the science of toxicology*. New Haven: Yale University Press.

Deguine, J.-P., P. Ferron, and D. Russell. 2009. *Crop protection: from agrochemistry to agroecology*. Enfield, NH: Science Publishers.

Domínguez, D., and P. Sabatino. 2010. La muerte que viene en el viento: La problemática de la contaminación por efecto de la agricultura transgénica en Argentina y Paraguay. In *Los señores de la soja*, ed. Ana Lucía Bravo, 31–122. Buenos Aires: CLACSO.

Evia Bertullo, V. 2018. Saberes y experiencias sobre la exposición a plaguicidas entre mujeres que residen en contextos agrícolas en Soriano, Uruguay. *Revista Trama* 9: 13–35.

Fenton, S. E., A. Ducatman, A. Boobis, J. C. DeWitt, C. Lau, C. Ng, J. S. Smith, and S. M. Roberts. 2021. Per- and polyfluoroalkyl substance toxicity and human health review: current state of knowledge and strategies for informing future research. *Environmental Toxicology and Chemistry* 40(3): 606–630. https://doi.org/10.1002/etc.4890.

Galt, R. E. 2008. Beyond the circle of poison: significant shifts in the global pesticide complex, 1976–2008. *Global Environmental Change* 18(4): 786–799. https://doi.org/10.1016/j.gloenvcha.2008.07.003.

Galt, R. E. 2009. It just goes to kill Ticos': national market regulation and the political ecology of farmers' pesticide use in Costa Rica. *Journal of Political Ecology* 16(1): 1–33. https://doi.org/10.2458/v16i1.21689.

Galt, R. E. 2013. From *Homo economicus* to complex subjectivities: reconceptualizing farmers as pesticide users. *Antipode* 45(2): 336–356. https://doi.org/10.1111/j.1467-8330.2012.01000.x.

Galt, R. E. 2014. *Food systems in an unequal world: pesticides, vegetables, and agrarian capitalism in Costa Rica*. Tucson: University of Arizona Press.

Gould, F., Z. S. Brown, and J. Kuzma. 2018. Wicked evolution: can we address the sociobiological dilemma of pesticide resistance? *Science* 360(6390): 728–732. https://doi.org/10.1126/science.aar3780.

Guthman, J. 2019. *Wilted: pathogens, chemicals, and the fragile future of the strawberry industry*. Oakland, CA: University of California Press.

Guthman, J., and B. Mansfield. 2013. The implications of environmental epigenetics. *Progress in Human Geography* 37: 486–504. https://doi.org/10.1177/0309132512463258.

Haggblade, S., B. Minten, C. Pray, T. Reardon, and D. Zilberman. 2017. The herbicide revolution in developing countries: patterns, causes, and implications. *The European Journal of Development Research* 29: 533–559. https://doi.org/10.1057/s41287-017-0090-7.

Hall, S. 1980. Race, articulation and societies structured in dominance. In *Sociological theories: race and colonialism*, 305–345. Poole, England: UNESCO.

Hals, T. 2021. Bayer to rethink Roundup in U.S. residential market after judge nixes $2 bln settlement. *Reuters*, May 27, 2021, sec. Healthcare & Pharmaceuticals. https://www.reuters.com/business/healthcare-pharmaceuticals/us-judge-rejects-bayers-2-bln-deal-resolve-future-roundup-lawsuits-2021-05-26/. Accessed June 28, 2023.

Harrison, J. L. 2011. *Pesticide drift and the pursuit of environmental justice*. The MIT Press.

Hart, G. 2018. Relational comparison revisited: marxist postcolonial geographies in practice. *Progress in Human Geography* 42(3): 371–394.

He, G., L. Zhang, A. P. J. Mol, T. Wang, and Y. Lu. 2014. Why small and medium chemical companies continue to pose severe environmental risks in rural China. *Environmental Pollution* 185(February): 158–167. https://doi.org/10.1016/j.envpol.2013.10.041.

Heap, I., and S. O. Duke. 2018. Overview of glyphosate-resistant weeds worldwide. *Pest Management Science* 74(5): 1040–1049. https://doi.org/10.1002/ps.4760.

Hepler-Smith, E. 2019. Molecular bureaucracy: toxicological information and environmental protection. *Environmental History* 24(3): 534–560. https://doi.org/10.1093/envhis/emy134.

Hetherington, K. 2020. *The government of beans: regulating life in the age of monocrops*. Durham, London: Duke University Press.

Hu, Z., and S. Rahman. 2016. Beyond a bottle of liquid: Pesticide dependence in transitional rural China. *The International Journal of Justice and Sustainability* 21(8): 919–938. https://doi.org/10.1080/13549839.2015.1050657.

IHS Markit. Various years. M&A annual update. Proprietary data, unpublished.

IHS Markit. 2020a. *Historic herbicide data*. Proprietary Data, unpublished.

IHS Markit. 2020b. *The generic agrochemical market 2018. 249. Topical insight & analysis from Phillips McDougall*. AgriFuture.

IHS Markit. 2021. *Top 20 2021*. Crop science special supplement.

Jaeger, J. W., I. H. Carlson, and W. P. Porter. 1999. Endocrine, immune, and behavioral effects of aldicarb (carbamate), atrazine (triazine) and nitrate (fertilizer) mixtures at groundwater concentrations. *Toxicology and Industrial Health* 15(1–2): 133–151. https://doi.org/10.1177/074823379901500111.

Jansen, K. 2008. The unspeakable ban: the translation of global pesticide governance into honduran national regulation. *World Development* 36(4): 575–589. https://doi.org/10.1016/j.worlddev.2007.04.017.

Jansen, K. 2017. Business conflict and risk regulation: understanding the influence of the pesticide industry. *Global Environmental Politics* 17(4): 48–66. https://doi.org/10.1162/GLEP_a_00427.

Jansen, K., and M. Dubois. 2014. Global pesticide governance by disclosure: prior informed consent and the Rotterdam Convention. In *Transparency in global environmental governance: critical perspectives*, eds. A. Gupta, and M. Mason. 107–131. Cambridge, Mass: The MIT Press.

Johnson, H. 2018. *International agricultural law and policy: a rights-based approach to food security*. Edward Elgar Publishing.

Kunin, J., and P. A. Lucero. 2020. Percepción social del riesgo y dinámicas género en la producción agrícola basada en plaguicidas en la pampa húmeda Argentina. *Sexualidad, salud y sociedad (Rio de Janeiro)* 35 (October): 58–81. https://doi.org/10.1590/1984-6487.sess.2020.35.04.a.

Lapegna, P. 2016. *Soybeans and power: genetically modified crops, environmental politics, and social movements in Argentina*. New York: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780190215132.001.0001.

Lapegna, P., and J. Kunin. 2023. Ambiguities at sites of acceptance: Agrarian neoliberalism and herbicide exposure in Argentina. *Environmental Justice* 16(1): 82–88. https://doi.org/10.1089/env.2021.0104.

Leguizamón, A. 2020. *Seeds of power: environmental injustice and genetically modified soybeans in Argentina*. Durham: Duke University Press.

Li, D. 2022. China price index: The impact of Sichuan's power restriction and historical high temperature on glyphosate, glufosinate. AgriBusiness Global. September 19, 2022. https://www.agribusinessglobal.com/agrochemicals/china-price-index-the-impact-of-sichuans-power-restriction-and-historical-high-temperature-on-glyphosate-glufosinate/. Accessed June 28, 2023.

Liboiron, M. 2021. *Pollution is colonialism*. Durham: Duke University Press.

Liboiron, M., M. Tironi, and N. Calvillo. 2018. Toxic politics: acting in a permanently polluted world. *Social Studies of Science* 48(3): 331–349. https://doi.org/10.1177/0306312718783087.

Lukowicz, C., S. Ellero-Simatos, M. Régnier, A. Polizzi, F. Lasserre, A. Montagner, Y. Lippi, E. L. Jamin, J. F. Martin, C. Naylies, C. Canlet, L. Debrauwer, J. Bertrand-Michel, T. Al Saati, V. Théodorou, N. Loiseau, L. Mselli-Lakhal, H. Guillou, and L. Gamet-Payrastre. 2018. Metabolic effects of a chronic dietary exposure to a low-dose pesticide cocktail in mice: sexual dimorphism and role of the constitutive androstane receptor. *Environmental Health Perspectives* 126(6): 067007. https://doi.org/10.1289/EHP2877.

Luna, J. K. 2018. Getting out of the dirt: racialized modernity and environmental inequality in the cotton sector of Burkina Faso. *Environmental Sociology* 4(2): 221–234. https://doi.org/10.1080/23251042.2017.1396657.

Luna, J. K. 2020. Pesticides are our children now': cultural change and the technological treadmill in the Burkina Faso cotton sector. *Agriculture and Human Values* 37: 449–462. https://doi.org/10.1007/s10460-019-09999-y.

Mansfield, B. 2021. Deregulatory science: Chemical risk analysis in Trump's EPA. *Social Studies of Science* 51(1): 28–50. https://doi.org/10.1177/0306312720970284.

Marquez, E., M. Ishii-Eiteman, and K. Schafer. 2020. Drift catchers combatting pesticide power. In *Bite back: people taking on corporate food and winning*, eds. S. Jayaraman, and K. De Master. 63–72. Oakland, CA: University of California Press.

Marrone, P. G. 2007. Barriers to adoption of biological control agents and biological pesticides. *CABI Reviews* 2007 (September): 12 pp. https://doi.org/10.1079/PAVSNNR20072051.

McMichael, P. 2013. *Food regimes and agrarian questions*. Agrarian Change & Peasant Studies. Practical Action Publishing.

Meghani, Z., and J. Kuzma. 2011. The 'revolving door' between regulatory agencies and industry: a problem that requires reconceptualizing objectivity. *Journal of Agricultural and Environmental Ethics* 24(6): 575–599. https://doi.org/10.1007/s10806-010-9287-x.

Mera-Orcés, V. 2001. Paying for survival with health: potato production practices, pesticide use and gender concerns in the ecuadorian highlands. *The Journal of Agricultural Education and Extension* 8(1): 31–40. https://doi.org/10.1080/13892240185300061.

Mesnage, R., G. Renney, G.-E. Séralini, M. Ward, and M. N. Antoniou. 2017. Multiomics reveal non-alcoholic fatty liver disease in rats following chronic exposure to an ultra-low dose of roundup herbicide. *Scientific Reports* 7(1): 39328. https://doi.org/10.1038/srep39328.

Moseley, W. G., M. A. Schnurr, and R. Bezner-Kerr. eds. 2017. *Africa's green revolution: critical perspectives on new agricultural technologies and systems*. New York: Routledge.

Mostafalou, S., and M. Abdollahi. 2017. Pesticides: an update of human exposure and toxicity. *Archives of Toxicology* 91(February): 549–599. https://doi.org/10.1007/s00204-016-1849-x.

Müller, B. 2021. Glyphosate—a love story: ordinary thoughtlessness and response-ability in industrial farming. *Journal of Agrarian Change* 21(1): 160–179. https://doi.org/10.1111/joac.12374.

Murphy, M. 2006. *Sick building syndrome and the problem of uncertainty: environmental politics, technoscience, and women workers*. Durham: Duke University Press.

Nash, L. 2008. Purity and danger: historical reflections on the regulation of environmental pollutants. *Environmental History* 13(4): 651–658.

Navas, G. 2022. 'If there's no evidence, there's no victim': Undone science and political organisation in marginalising women as victims of DBCP in Nicaragua. *The Journal of Peasant Studies*, March, 1–24. https://doi.org/10.1080/03066150.2021.2024517.

Nixon, R. 2011. *Slow violence and the environmentalism of the poor*. Cambridge, Mass: Harvard University Press.

Nørgaard, K. B., and N. Cedergreen. 2010. Pesticide cocktails can interact synergistically on aquatic crustaceans. *Environmental Science & Pollution Research* 17: 957–967. https://doi.org/10.1007/s11356-009-0284-4.

Oliveira, G. L. T., C. He, and J. Ma. 2020. Global-local interactions in agrochemical industry: relating trade regulations in Brazil to environmental and spatial restructuring in China. *Applied Geography* 123: 102244. https://doi.org/10.1016/j.apgeog.2020.102244.

Palmisano, T. 2018. Las agriculturas alternativas en el contexto del agronegocio: Experiencias en la Provincia de Buenos Aires, Argentina. *Estudios sociales. Revista de alimentación contemporánea y desarrollo regional* 28 (51). https://doi.org/10.24836/es.v28i51.513.

PAN Pesticide Action Network. 2022. PAN international consolidated list of banned pesticides. Pesticide Action Network. https://pan-international.org/pan-international-consolidated-list-of-banned-pesticides/. Accessed June 28, 2023.

Patel, R. 2013. The long green revolution. *The Journal of Peasant Studies* 40(1): 1–63. https://doi.org/10.1080/03066150.2012.719224.

Phillips McDougall. 2016. The cost of new agrochemical product discovery, development and registration in 1995, 2000, 2005-8 and 2010–2014. R&D Expenditure in 2014 and Expectations for 2019. A Consultancy Study for CropLife International, CropLife America and the European Crop Protection Association. Midlothian, Scotland, United Kingdom. https://croplife.org/wp-content/uploads/2016/04/Cost-of-CP-report-FINAL.pdf. Accessed June 28, 2023.

Qiu, D. 2015. Analysis of the development situation and trends of biological pesticides in China. *Chinese Journal of Biological Control* 31(5): 679–684. https://doi.org/10.16409/j.cnki.2095-039x.2015.05.008.

Rezende, E. C. N., F. M. Carneiro, J. Ballico de, Moraes, and I. J. Wastowski. 2021. Trends in science on glyphosate toxicity: a scientometric study. *Environmental Science and Pollution Research* 28(40): 56432–56448. https://doi.org/10.1007/s11356-021-14556-4.

Richardson, T., and G. Weszkalnys. 2014. Introduction: resource materialities. *Anthropological Quarterly* 87(1): 5–30.

Ríos-González, A., K. Jansen, and H. J. Sánchez-Pérez. 2013. Pesticide risk perceptions and the differences between farmers and extensionists: towards a knowledge-in-context model. *Environmental Research* 124(July): 43–53. https://doi.org/10.1016/j.envres.2013.03.006.

Robbins, P. 2007. *Lawn people: how grasses, weeds, and chemicals make us who we are*. Philadelphia: Temple University Press.

Romero, A. M. 2022. *Economic poisoning: industrial waste and the chemicalization of american agriculture*. Oakland, CA: University of California Press.

Romero, A. M., J. Guthman, R. E. Galt, M. Huber, B. Mansfield, and S. Sawyer. 2017. Chemical geographies. *GeoHumanities* 3(1): 158–177. https://doi.org/10.1080/2373566X.2017.1298972.

S&P Global. 2023. Directory of chemical producers. Proprietary data, unpublished.

Schmidt, M., V. Toledo López, M. Tobías, E. Grinberg, and G. Merlinsky. 2022. Conflictividad socio-ambiental por uso de agroquímicos en salta, Santiago Del Estero y Santa Fe, Argentina. *Ciência & Saúde Coletiva* 27(3): 1061–1072. https://doi.org/10.1590/1413-81232022273.04852021.

Schreinemachers, P., and P. Tipraqsa. 2012. Agricultural pesticides and land use intensification in high, middle and low income countries. *Food Policy* 37(6): 616–626. https://doi.org/10.1016/j.foodpol.2012.06.003.

Schurman, R., and W. A. Munro. 2010. *Fighting for the future of food: activists versus agribusiness in the struggle over biotechnology*. Minneapolis, MN: University of Minnesota Press.

Schwartz, N. A., C. A. von Glascoe, V. Torres, L. Ramos, and C. Soria-Delgado. 2015. Where they (live, work and) spray': Pesticide exposure, childhood asthma and environmental justice among mexican-american farmworkers. *Health & Place* 32(March): 83–92. https://doi.org/10.1016/j.healthplace.2014.12.016.

Senanayake, N. 2022. We spray so we can live': agrochemical kinship, mystery kidney disease, and struggles for health in dry zone Sri Lanka. *Annals of the American Association of Geographers* 112(4): 1047–1064. https://doi.org/10.1080/24694452.2021.1956295.

Shapiro, N. 2015. Attuning to the chemosphere: domestic formaldehyde, bodily reasoning, and the chemical sublime. *Cultural Anthropology* 30(3): 368–393. https://doi.org/10.14506/ca30.3.02.

Shattuck, A. 2021a. Generic, growing, green?: the changing political economy of the global pesticide complex. *The Journal of Peasant Studies* 48(2): 231–253. https://doi.org/10.1080/03066150.2020.1839053.

Shattuck, A. 2021b. Risky subjects: embodiment and partial knowledges in the safe use of pesticide. *Geoforum* 123: 153–161. https://doi.org/10.1016/j.geoforum.2019.04.029.

Shattuck, A., M. Werner, F. Mempel, Z. Dunivin, and R. E. Galt. 2023. Global pesticide use and trade database (GloPUT): new estimates show pesticide use trends in low-income countries substantially underestimated. *Global Environmental Change* 81: 102693.

Sponsler, D. B., C. M. Grozinger, C. Hitaj, M. Rundlöf, C. Botías, A. Code, and E. V. Lonsdorf et al. 2019. Pesticides and pollinators: a socioecological synthesis. *Science of The Total Environment* 662(April): 1012–1027. https://doi.org/10.1016/j.scitotenv.2019.01.016.

Stein, S., and J. Luna. 2021. Toxic sensorium: Agrochemicals in the african anthropocene. *Environment and Society: Advances in Research* 12: 87–107.

Stobbart, D. 2021. The global agrochemical market in 2021. *IHS Markit crop science market analysis & data* November 2021.

Stobbart, D., and S. Rana. 2022. Vulnerable supply chain: crop science developments. Presented at the IHS Markit Agribusiness Value Chain Forum, June 8.

Thrupp, L. A. 1988. Pesticides and policies: approaches to pest-control dilemmas in Nicaragua and Costa Rica. *Latin American Perspectives* 15(4): 37–70. https://doi.org/10.1177/0094582X8801500403.

Tognoni, G. ed. 1997. *Manual de epidemiologia comunitaria*. CECOMET.

Tomenson, J. A., and G. A. Matthews. 2009. 6,300 smallholder applicators in 24 different countries. *International Archives of*

Occupational and Environmental Health 82(August): 935–949. https://doi.org/10.1007/s00420-009-0399-4. Causes and types of health effects during the use of crop protection chemicals: Data from a survey of over.

Tuck, E. 2009. Suspending damage: a letter to communities. *Harvard Educational Review* 79(3): 409–428. https://doi.org/10.17763/haer.79.3.n0016675661t3n15.

Valbuena, D., M. Cely-Santos, and D. Obregón. 2021. Agrochemical pesticide production, trade, and hazard: narrowing the information gap in Colombia. *Journal of Environmental Management* 286: 112141. https://doi.org/10.1016/j.jenvman.2021.112141.

Van den Bosch, R. 1989. *The pesticide conspiracy*. University of California Press.

Van der Ploeg, J. D. 2020. Farmers' upheaval, climate crisis and populism. *The Journal of Peasant Studies* 47(3): 589–605. https://doi.org/10.1080/03066150.2020.1725490.

Vogel, S. A. 2013. *Is it safe?: BPA and the struggle to define the safety of chemicals*. Berkeley: University of California Press.

Wargo, J. 1998. *Our children's toxic legacy: How science and law fail to protect us from pesticides*. Second Edition. New Haven; London: Yale University Press.

Warner, K. D. 2007. *Agroecology in action: extending alternative agriculture through social networks*. Cambridge, Mass: MIT Press: Food, Health, and the Environment.

Watts, M., and S. Williamson. 2015. *Replacing chemicals with biology: phasing out highly hazardous pesticides with agroecology*. Pesticide Action Network Asia and the Pacific.

Weir, D., and M. Schapiro. 1981. *Circle of poison: pesticides and people in a hungry world*. Oakland, CA: Institute for Food and Development Policy.

Werner, M., C. Berndt, and B. Mansfield. 2022. The glyphosate assemblage: herbicides, uneven development, and chemical geographies of ubiquity. *Annals of the American Association of Geographers* 112(1): 19–35. https://doi.org/10.1080/24694452.2021.1898322.

Whorton, J. C. 1974. *Before Silent Spring: pesticides and public health in pre-DDT America*. Princeton: Princeton University Press.

Williams, B. 2018. That we may live': pesticides, plantations, and environmental racism in the United States South. *Environment and Planning E: Nature and Space* 1(1–2): 243–267. https://doi.org/10.1177/2514848618778085.

Williams, B. 2021. The fabric of our lives'?: cotton, pesticides, and agrarian racial regimes in the U.S. South. *Annals of the American Association of Geographers* 111(2): 422–439. https://doi.org/10.1080/24694452.2020.1775542.

Williams, B., and J. M. Porter. 2022. Cotton, whiteness, and other poisons. *Environmental Humanities* 14(3): 499–521. https://doi.org/10.1215/22011919-9962827.

Williamson, S. 2003. Pesticide provision in liberalised Africa: Out of control? 126. Agricultural Research and Extension Network Paper. London: Overseas Development Institute. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=358c993e7ee62c2de5155a29e640467e5a56850d. Accessed June 28, 2023.

Woods, C. 2017. *Development arrested: the blues and plantation power in the Mississippi Delta*. London; New York: Verso Books.

World Health Organization, and United Nations Environment Programme, eds. 1990. *Public health impact of pesticides used in agriculture*. Geneva: World Health Organization.

Wright, A. 1986. Rethinking the circle of poison: the politics of pesticide poisoning among mexican farm workers. *Latin American Perspectives* 13(4): 26–59. https://doi.org/10.1177/0094582X8601300403.

Wright, A. 1990. *The death of Ramón González: the modern agricultural dilemma*. Austin: University of Texas Press.

Zhang, W., F. Jiang, and J. Ou. 2011. Global pesticide consumption and pollution: with China as a focus. *Proceedings of the International Academy of Ecology and Environmental Sciences* 1 (2): 125–44.

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