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Toxic trespass: Science, activism, and policy concerning chemicals in our bodies

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Exposure to chemical trespassers is ubiquitous for all people, with a daily onslaught of air particulates from factories and power plants, parabens in personal care products, phthalates and bisphenol (BPA) in consumer products, flame retardants in furniture, radiation from uranium mine tailings, polychlorinated biphenyls (PCBs) in fish and marine mammals, and trichloroethylene (TCE) from common industrial usage. The US Centers for Disease Control and Prevention's benchmark National Health and Nutrition Examination Survey (NHANES) shows how common it is for environmental chemicals to enter our bodies, and a large number of academic and advocacy household exposure and biomonitoring studies add to that knowledge (Centers for Disease Control and Prevention 2018). This is a *toxic trespass* of chemicals that violate our bodies and environment without permission (Redfield 1984; Malkan 2003; Schafer et al. 2004; Shamasunder and Morello-Frosch 2016). Toxic trespass has generated much conflict, affected policy making, spurred legislation, raised public awareness, attracted media coverage, and spawned social movement activity. Dealing with toxic trespass brings to light disputes between laypeople and professionals, citizens and governments, and among professionals, because the consequences of exposure are often poorly understood and because environmentally induced diseases are among the most prominent types of "contested illnesses" (Brown 2007). Toxic trespass often disproportionately impacts environmental justice (EJ) communities, because polluting facilities are concentrated in low-income communities and communities of color, and exposure to many chemicals through consumer products is also higher for marginalized populations (Helm et al. 2018; Mitro et al. 2018). Precisely because environmental diseases are so common in daily life and all aspects of the economy, these diseases have become highly politicized and have spurred much social movement activism.

In this chapter, we discuss the social and scientific discovery of environmental contaminants and the response by science, government, and social movements. We begin with a select history of how embodied contamination became an important issue, and then discuss how academics and progressive lay–professional alliances have altered traditional perspectives on science in order to place environmental health science in the service of those affected by contamination. As a case study for how these concerns are played out within a major contamination problem, we focus on per- and polyfluorinated compounds (PFAS), perhaps the most visible class of chemicals now coming to public attention. Our PFAS Project at Northeastern University's Social Science Environmental Health Research Institute (SSEHRI) has played a large role in community organizing and academic–community partnerships around PFAS, including collaborations at the transdisciplinary intersection of social and life sciences. Lessons from our case study can be applied to many other forms of toxic trespass from hazardous substances, and can demonstrate a framework of community-based participatory research and community-engaged research for social scientists and life scientists to effect change.

Theoretical understandings of science

Scientists and people impacted by environmental issues increasingly merge their efforts and expertise to use and critique existing science, while also developing and applying new research approaches. For individuals impacted by environmental health problems, whether localized sites of contamination or broader exposures through daily life and consumer products, science is a necessary tool to uncover and reduce toxic exposures, identify and alleviate associated health effects, and prevent future exposures. We use the term "science" to refer to the systematic collection of evidence and observations to describe and explain something about the world. While scientific authority rests on science being seen as "value-free and politically neutral" (Kinchy and Kleinman 2003, 380), most sociologists challenge the supposedly bright line between science and other areas of society, arguing that science is as much socially constructed as it is empirically based, since it is conducted by people with diverse social positions, and because science takes place within a social context (Gieryn 1983; Jasanoff et al. 1995).

Despite the increasing relevance of civic science (often called citizen science) and research conducted outside of traditional scientific institutions for environmental health research, scientific arguments and more formalized investigations are obligatory in fields like science policy, chemical product development, or environmental activism. The process of *scientization* refers to how scientific authority is increasingly valued and required for regulatory, legal, and social movement activities (Michaels and Monforton 2005; Morello-Frosch et al. 2006; Kinchy 2010). Participation in these scientized fields typically depends on *expertise*, or the in-depth and appropriately credentialed technical knowledge and experience that is particular to a topic, sector, or discipline. Highly scientized fields routinely exclude lay voices and the experiences of those directly impacted by risks, such as workers or residents who live near polluting facilities (Morello-Frosch et al. 2006).

Recent work in sociology and science and technology studies (STS), especially the *new political sociology of science* approach, has identified the networks, institutions, and power structures of inequality that affect the production and consumption of scientific knowledge and ignorance (Frickel and Moore 2006). In addition to power, disciplinary norms and practices contribute to socially produced gaps in scientific knowledge through both deliberate actions as well as unintentional, influential institutional logics (Hess 2009; Frickel et al. 2010; Kempler et al. 2011; Moore et al. 2011; Kleinman and Suryanarayanan 2012). Funding priorities are often set by federal agencies or the military and thus reflect elite priorities (Moore 2008), disciplines compete for intellectual territory and scarce grant dollars (Frickel and Gross 2005), and the research questions of interest to the government or industry often receive greater attention than those of interest to communities and non-elites (Hess 2009; Frickel et al. 2010).

Some uncertainty is inherent in the environmental health research process, related to choosing research questions or methods, interpreting scientific results, communicating results to multiple publics, and applying results for policy making (Cordner and Brown 2013). The length and complexity of exposure pathways, described below, make it very difficult to link exposures and disease outcomes, even if information is not intentionally concealed or strategically manipulated by responsible parties, as is often the case when industries attempt to delay recognition of their products' hazards using scientific arguments (Markowitz and Rosner 2002; Michaels 2008; Proctor and Schiebinger 2008; Oreskes and Conway 2010; Cordner 2016). All of these issues matter greatly for scholars working with impacted EJ communities, who have greater environmental hazards, combined with less resource to deal with those hazards.

As this section has shown, science is highly affected by social, political, economic, and ideological factors – all of those involving use of power by those in charge, and opposition to that power by those affected. To continue this train of thought, we now turn to the impact of social movements on environmental science and policy.

Social discovery and social movements

Rachel Carson's groundbreaking *Silent Spring* in 1962 ushered in the modern environmental movement by bringing mass public attention to environmental health effects of toxics. Carson showed how pesticides were serious hazards, causing morbidity and mortality in animals and humans (Carson 1962). Like many other pioneers in public health, Carson was sharply criticized by many for being unscientific and for attacking major economic sectors. Carson's work and the growing US environmental movement led to significant regulation of pesticides and other chemicals, and eventually to the passage of the National Environmental Protection Act and the establishment of the Environmental Protection Agency (EPA). Her work inspired a new generation of environmental activists largely concerned with ecological and animal effects. Although most readers paid less attention to human health concerns in the book, Carson made the first link to breast cancer and the role of endocrine disrupting compounds (EDCs), which would later be shown as central to many diseases and conditions.

The modern environmental movement gained additional support when hazardous waste under a school in Niagara Falls, New York in 1978 introduced human health as a central concern in an environmental crisis (Levine 1982; Gibbs 2011). Residents learned from state health officials that toxic chemicals permeated the Love Canal neighborhood because the city bought a dumpsite on which to build a school from Hooker Chemical Company for one dollar, with a clause guaranteeing no corporate liability. The revelation meshed with residents' awareness of having seen noxious substances oozing from the site and experiencing unusual health effects. As residents organized to learn more, they discovered high rates of miscarriages, birth defects, cancers, and chromosome damage (Levine 1982). Newly minted activists, with no scientific or social movement background, quickly learned the relevant science and took direct action by community organizing, demonstrating, organizing health studies, and demanding action by state and federal governments. The contamination at Love Canal prompted the creation of the Superfund Program by the US Environmental Protection Agency (EPA).

A few years later there was a similar occurrence in Woburn, Massachusetts, when TCE from W. R. Grace Chemicals and Beatrice Foods was dumped, leading to a childhood leukemia cluster. There, in addition to social discovery, residents worked with scientists to conduct a large health study that became a model for "popular epidemiology," in which laypeople, often residents in contaminated communities, link illness rates and clusters with local pollution – in this case TCE (Brown and Mikkelsen 1990). Soon it was clear that a widespread toxic crisis was stimulating a new toxic waste movement (Brown and Masterson-Allen 1993), eventually leading to countless communities around the country taking similar action when faced with toxic contamination.

Since many of the contaminated communities were in minority and low-income areas, the environmental justice movement developed, linking institutionalized racism to environmental contamination (Bullard 1990; Mohai et al. 2009; Agyeman et al. 2016). The EJ movement took things a step further by incorporating the centrality of racial and class structures. The discovery of toxic trespass in EJ communities is particularly important because these communities typically face higher burdens of exposure to pollution and negative associated health outcomes. EJ is fundamentally about the distribution of environmental hazards and the rights of all people – in particular those most affected by environmental hazards – to be recognized and participate in environmental decision-making processes (Mohai et al. 2009; Schlosberg 2009; Agyeman et al. 2016).

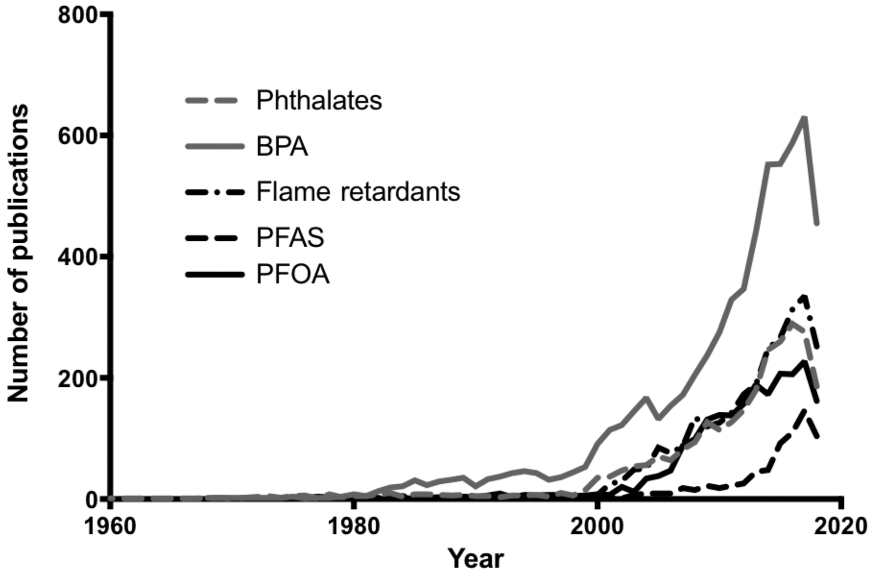
How, then, do affected residents uncover diseases and conditions in their midst, and link them to environmental factors? Despite the general absence of appropriate surveillance and epidemiological activity, it is striking that ordinary citizens can make the relevant connections. They, along with a growing cadre of forward-looking scientists and health professionals, have helped to bring to public attention to the many *contested illnesses* that are now prevalent (Brown, Morello-Frosch, and Zavestoski 2012). Describing an emerging public understanding of the endocrine disruptor hypothesis, which sought to explain many of the newly contested illnesses, Krimsky (2000) defined *social discovery* as the growing awareness of a previously unrecognized or poorly understood social problem, disease, environmental hazard, or social phenomenon. The production of a *public hypothesis* – the growing awareness by the lay public of a previously unrecognized or poorly understood social problem, disease, environmental hazard, or social phenomenon – is not necessarily incremental or inevitable, but rather involves struggles between countervailing forces under public scrutiny (Krimsky 2000). People may develop concerns about environmentally induced diseases when they observe illness clusters, as noted above in Woburn, especially if there is a known, nearby contamination source such as an abandoned toxic waste site, operating incinerator, or chemical factory. At other times, people learn about increased cancer rates from annual cancer registry reports, which is what led to major attention to research on environmental factors and breast cancer on Long Island, New York and Cape Cod, Massachusetts (Brown et al. 2006). Sometimes people notice health effects in animals, and become concerned that humans too will be affected. For example, the Tennant family in the Mid-Ohio Valley uncovered toxic perfluorooctanoic acid (PFOA) contamination on land used by DuPont after their entire cattle herd died (Lyons 2007). The Tennant family sued DuPont and eventually won a major class action lawsuit. One result of the case was the C8 Study, a groundbreaking 69,000-person epidemiological study that linked PFOA to six diseases and conditions and raised national attention on the entire class of per- and polyfluorinated compounds (PFAS), making it one of the most prominent group of contaminants today (Frisbee et al. 2009). We will go into detail on that case later.

Social discovery meets scientific discovery

Activist attention has combined with new scientific discovery to focus attention on contaminants that were previously understudied or emerging. As a result, rapid shifts have occurred in cases of emerging contaminants, for example PFAS, flame retardants, BPA, PFOA, and phthalates, as shown in Figure 1.1. Some scientists increasingly saw the need to put their talent to work to solve pressing problems that affected human health, while others sought to counter industry-dominated science that covered up hazards. This increased research has mobilized regulatory changes at the state and federal level, amplified community stories, and empowered the formation of community-based social movement organizations that continue to push for increased research funding, new and larger studies, transparency, and a seat at the decision-making table.

Exposure pathway

Identifying toxic trespass when it occurs requires defining and evaluating the *exposure pathway*, the link between the exposure source and how people are exposed to environmental contaminants (Maxwell 2009). The elements of the exposure pathway include the source (such as landfills, spills, or factory emission stacks), fate and transport (how contaminants travel through and act in different environmental media once released), the exposure point (household dust, contaminated drinking water), and the exposure route (inhalation, dermal, or ingestion). An important link between exposure pathways and disease outcomes



Note: Search terms used in PubMed were: *PFAS* (Title/Abstract), *PFOA* (Title/Abstract), *BPA* (Title/Abstract), *Flame retardants* (Title/Abstract), and *Phthalates* (Title/Abstract). The number of publications matching these terms were plotted by year. Publications prior to 1960 are not depicted in the graph above. This cut-off resulted in the exclusion of only four phthalate publications.

1.1 Published scientific research on various emerging contaminants. Research on emerging contaminants has increased over the last two decades.

is understanding *internal* exposures and toxicity. In addition to identifying disease endpoints in studies, toxicologists can measure adverse effects at the molecular and tissue level such as genetic mutations, altered immune responses, altered hormone responses, and changes in tissue morphology that can lead to disease. The toxicity of a chemical depends on many factors: the timing of exposure from preconception through childhood and adulthood; where the chemical is present in the body; how much is present; duration of exposure; genetic susceptibility; and interaction with social variables like stress, green space, and exposure to violence. Many chemicals are removed from the body quickly, thanks to our primary defense against foreign chemicals, the liver (Casarett et al. 2001). However, compounds that tend not to degrade, including PCBs, DDT (dichlorodiphenyltrichloroethane), PFAS, many flame retardants, and other industrial by-products, can accumulate in our bodies and the food chain because of their chemical and physical properties (Casarett et al. 2001).

Transdisciplinary social science–environmental work

To study complex environmental phenomena like the exposure pathway, sociologists and other social scientists are increasingly engaged in transdisciplinary collaborations in environmental health fields (Hoover et al. 2015; Finn and Collman 2016; Matz et al. 2016). With a strong focus on environmental inequalities, research has moved away from isolated disciplinary silos toward engaged, transdisciplinary work in partnership with impacted communities to investigate exposures and health effects, mitigate hazards, influence environmental policy, and prevent new exposures. In such collaborations, sociologists and other EJ researchers become active members of environmental health research teams rather than just observers. Hoover et al. (2015) describe this as a shift from "social science *of* environmental health," which investigates environmental health crises, exposures, contamination, and disasters, and by examining the production of scientific knowledge around environmental health issues from a political economic or EJ perspective (e.g., Edelstein 1988; Bullard 1990; Kroll-Smith and Couch 1990; Faber 2008), to "social science *with* environmental health." This work involves directly collaborating in environmental health research projects with health scientists, residents, and community-based organizations (Hoover et al. 2015).

For one example, we can look at the long-term relationship between the community-based science organization Silent Spring Institute; academic researchers at Brown University, Northeastern University, and UC-Berkeley; and the community activist group Communities for a Better Environment (in northern California). A formative element of that work stemmed from the response to participants' calls for sharing environmental health data from biomonitoring and household exposure studies. The partners developed best practices and built an ethical framework for the individual and community report-back of environmental health data, which was quite uncommon at the time (many researchers and Institutional Review Boards believed that such data would "worry" participants). In both conducting and studying the process of report-back as it took place in Cape Cod, Massachusetts and in Richmond and Bolinas, California, the team reflexively engaged with the community and research participants to (1) understand the individual and collective needs of participants related to their environmental health data; (2) understand how taking part in research and receiving data influences the creation of shared definitions of exposure; (3) investigate how personal and collective histories influence the understanding of data; and (4) understand generally how receiving environmental health data influences participants personally and politically (Adams et al. 2011; Brown et al. 2012).

These transdisciplinary collaborations are challenging for social scientists and environmental health scientists alike because of the additional layers of collaboration, risk communication, and transdisciplinary communication required. Few environmental health scientists receive formal training in the nuances of environmental communication and risk issues surrounding contaminated sites. Likewise, few social scientists studying environmental health issues receive formal training in the environmental health sciences they are studying and must learn to communicate with environmental health scientists. This cross-training is especially important when social scientists and environmental health scientists are working with EJ groups and communities. Such work should be guided by EJ principles, including deep and meaningful involvement of marginalized populations, the protection of all populations from environmental hazards, an emphasis on prevention and precautionary approaches as the best risk mitigation, and redress of disproportionate exposures (Bullard 2008).

Biomonitoring and household exposure research

Biomonitoring involves testing for the presence and accumulation of chemicals or chemical breakdown products in the human body, often using blood or urine. Such studies can provide insight on our internal exposure and the persistence of chemicals in our body. Together, biomonitoring studies and exposure measurements in various media, such as air, water, household dust, or soil, enable scientists to estimate our exposure. As noted above, the CDC's NHANES biomonitoring project has played a central role in showing exposure in a sample of the US population, expanding from 21 chemicals in 2001 to 265 chemicals in 2015 (Centers for Disease Control and Prevention 2018).

Academic researchers have also conducted extensive biomonitoring, often seeking to link exposure with health effects. Much academic research involves studies conducted by university researchers with the primary aim of peer-reviewed publications. Exposure scientists and environmental epidemiologists have increasingly found this an interesting area, and some have been outspoken about using their research for public betterment via regulation and product changes (Dodson et al. 2017; Zota et al. 2017; Helm et al. 2018).

Other academics have embraced community-based participatory research (CBPR), in which scientists and community groups co-create research questions, methods, and dissemination, and control over all aspects of the research process is shared with community partners. Goals of CBPR projects include increased community engagement in research to generate more accurate scientific knowledge, improved public trust and understanding of environmental health science, utilization of culturally and socially appropriate interventions, improved public health decisions, policy changes, and reductions in environmental injustice (O'Fallon and Dearry 2002; Wallerstein et al. 2017).

Silent Spring Institute's household exposure study on Cape Cod, mentioned above, provides an example of a CBPR study that tested for household exposure to environmental contaminants. The study focused on exposure to EDCs, including the first indoor measures for 30 compounds, and identified a wood floor finish as a widespread ongoing source of PCBs (Rudel et al. 2003, 2008). In subsequent exposure monitoring, Silent Spring expanded the household exposure study to Richmond, California to measure exposure to similar chemicals in a poor, minority community (Brody et al. 2009). What was most striking was the pronounced toxic trespass of the indoor environment with chemicals from heavy oil combustion and the disproportionate cumulative impact of pollution in the Richmond community from exposures due to both industrial and household sources (Brody et al. 2009; Rudel et al. 2010). These studies activated and expanded community engagement around EJ issues and encouraged community members to think in new ways about sources of chemicals around them. Empowered community members shared their exposure data to inform policy changes (Brown et al. 2012).

Civic science (aka "citizen science" and "community science") involves academic–community partnerships and community monitoring (Irwin 1995; Corburn 2005; Kinchy 2017). In addition to gathering and integrating more scientific observations than would be possible in traditionally funded and traditionally operated projects, citizen science has the capacity to democratize the research process. Among the many examples of how citizen science has contributed to biomonitoring and exposure research, popular epidemiology has been used by contaminated communities in the following ways: residents in Woburn, Massachusetts conducted health studies of childhood leukemia (Brown 1987); the Louisiana Bucket Brigade monitored various petroleum emissions (Allen 2003; Ottinger 2010); farmworkers have measured pesticide drift (Harrison 2011); Gulf Coast residents have used balloon mapping to monitor the BP oil spill; and residents have used inexpensive hydrogen sulfide detectors using photographic paper to see the toxic hazards from fracking (Wylie and Thomas 2014).

In addition to citizen science projects, *advocacy biomonitoring* involves measuring people's exposures with the purpose of developing knowledge to be used for activism and public outreach (Morello-Frosch et al. 2009). Pioneered by the Environmental Working Group's "Body Burden" study of 10 individuals (Houlihan et al. 2003), advocacy biomonitoring involves laypeople, working through activist organizations to produce important environmental health science. These projects are often initiated by non-scientists, who contract outside laboratories to conduct the chemical analyses. Sample sizes are small, typically ranging from three to thirty people, so results are not intended to be analyzed statistically but rather to illustrate the chemicals present in ordinary people. In many advocacy biomonitoring projects, people publicly share their chemical exposure data along with photographs and biographies. Projects typically target chemicals that are less studied and poorly regulated. In participating in these studies, people emphasize the importance of going beyond individual solutions to press for regulatory and corporate reform in order to reduce exposures (Washburn 2013; Morello-Frosch and Brown 2014; MacKendrick 2018). A new variant, conducted by Silent Spring Institute, uses crowdsourced biomonitoring gathered from individuals using the Detox Me Action Kit, in which people pay to participate in urine biomonitoring of 10 emerging contaminants (Silent Spring Institute 2018). In the current Trump era, citizen science and community-based research face increasing attacks from industry and regulatory bodies attempting to undermine the use of and invalidate results from these studies. Under the guise of science transparency, the community-based and advocacy biomonitoring studies that are integral in the scientific and social discovery of emerging contaminants are often called into question by misleading chemical regulation policies, such as the recently proposed transparency in regulatory science rule and rejection of a ban on the pesticide chlorpyrifos (Paris et al. 2017; Berg et al. 2018; Dillon et al. 2018).

The history of exposure science, environmental health activism, and biomonitoring and household exposure research discussed so far provide us with an overview of toxic trespass. With that in hand we now turn to a case study of a major new set of chemical contaminants, a case that shows the many intersections between environmental activism, scientific discovery, and the many social, political, and economic factors that are central to chemical hazards.

Case study: per- and polyfluorinated compounds

PFAS are a class of chemicals that has become a contaminant of concern for residents and activists, regulators, and many industry representatives due to its persistence, widespread exposure, and contamination. The social and scientific discovery of PFAS touches on many of the issues we have raised so far, including the scientific challenges of establishing an exposure-to-disease pathway, the need for transdisciplinary and collaborative research, and the two-way relationship between scientific research and public health advocacy. Our PFAS Project team of 10 researchers at Northeastern University's Social Science

Environmental Health Research Institute – faculty, postdocs, graduate students, and undergraduates – has been at the forefront of raising awareness of PFAS contamination and documenting the social discovery of this class of chemicals (Cordner et al. 2016, 2019). We have been working for three years to make known the extent and health effects of PFAS contamination by publicly tracking new cases of discovery in real time and making this information accessible on an interactive map; aiding community groups and local and state governments in remediation, research, and regulatory action; engaging with journalists who publicize the problem; giving presentations at conferences and webinars of environmental activists and educators; organizing national conferences; and facilitating a national coalition of PFAS activist groups. Much of this work involves efforts with Silent Spring Institute, a collaborator on this and other projects for over a decade. Especially significant is the role of doctoral students and postdocs who are supported by a joint Northeastern SSEHRI/Silent Spring training program funded by the National Institute of Environmental Health Sciences, part of the National Institutes of Health.

PFAS are an unusual chemical class because of their dual nature of contamination: the site-specific contaminated communities, and the ubiquitous low-level contamination of everyday life. This sets them apart both from other occupational/contaminated community sites where consumer exposure is rare, and from other emerging chemicals like flame retardants without identified contaminated communities. However, some aspects of the PFAS story are common among other emerging contaminants. In particular, PFAS are widely used and sometimes their use is well known (e.g., in Teflon and Scotchguard), while other times it is invisible and unknown (e.g., in dental floss and other personal care products).

PFAS are a class of nearly 5,000 human-made fluorinated chemicals containing chains of carbon and fluorine atoms widely used in industrial processes and consumer goods (Organisation for Economic Co-operation and Development 2018). The most widely known PFAS chemicals are perfluoroocatanoic acid (PFOA), which was used to manufacture Teflon coatings, and perfluorooctane sulfonate (PFOS), used in Scotchgard fabric protectors, firefighting foam, and in semiconductor devices. PFAS are also widely used in aqueous firefighting foam (AFFF) used at military sites, airports, and firefighting training facilities. PFOA was first developed by DuPont chemists in 1938 and studied by DuPont for toxicological and exposure concerns starting in the 1960s (Lyons 2007), but significant awareness of PFAS within the regulatory and academic science community did not occur until decades later. Figure 1.1 (above) shows the rapid increases in publications on PFOA and PFAS since 2000. PFAS's historical legacy and social construction is similar to flame retardants in that problems early on in the 1970s led to a small amount of action, such as regulation, yet received little attention for decades (Cordner 2016). A more recent rapid rise in both research and public interest in PFAS is likely due to a combination of factors, including increased widespread contamination in communities, national exposure studies documenting widespread water contamination, new state and federal regulations, and improvements in technologies for detecting and identifying new types of PFAS chemicals for study.

Epidemiological and toxicological research has linked PFAS exposure to multiple health conditions. Following over 50 years of toxic trespass and a $650 million legal settlement by DuPont, the C8 Study's 69,000-participant epidemiological study in the Mid-Ohio Valley linked PFOA exposure with high cholesterol, ulcerative colitis, thyroid disease, testicular and kidney cancers, and pregnancy-induced hypertension (C8 Science Panel). Research apart from the C8 Study has found other suspected health impacts that include endocrine disruption, obesity, reproductive problems, birth defects, other types of cancer, stroke, and developmental problems in children (Lau 2015).

Apart from the well-known Mid-Ohio Valley situations, numerous communities have similarly experienced widespread PFAS contamination of drinking water due to their proximity to manufacturing sites, including Decatur AL (3M and Daikin), the Cape Fear River area in North Carolina (Chemours), Hoosick Falls, New York and North Bennington, Vermont (Saint Gobain Performance Plastics), and Cottage Grove, Minnesota (3M). Learning about exposure routes and potential health effects for these and many other sites has been hampered by decades of corporate deception in hiding data on PFAS hazards. Leading PFAS manufacturer 3M learned as early as 1970 from internal studies that workers were widely exposed to PFOA (Lyons 2007). Later epidemiological studies found that PFOA exposure increased workers' mortality rates, including doubling their chance of dying from prostate cancer and stroke (Lindstrom et al. 2011).

Widespread exposure to PFAS had been long linked to industry releases at manufacturing sites, but recent years have seen discovery at military, airport, and other sites where PFAS-containing AFFFs were used in flammable liquid fuel fires or for firefighter training. The US Department of Defense (DoD) has identified 401 current or former military sites with known or suspected PFAS contamination, including 126 sites with PFOA or PFAS levels above the EPA health advisory level, mostly due to the use of AFFFs for training or fire suppression (Sullivan 2018).

In some cases of contamination on military bases, officials have been supportive of research on PFAS fate and transport, exposure assessment, and remediation, and have quickly provided clean drinking water to impacted residents when PFOA and/or PFOS are detected above the EPA's health guideline. This situation is unlike other military contamination instances, such as PCB contamination at Alaska's St Lawrence Island (Lerner 2012) or TCE contamination at Camp LeJeune (Bove et al. 2014), for two reasons. First, the activists generally have not been military service members or veterans, but affected civilians living on or near military bases, and hence their activism has been less constrained because they are not subject to the formal constraints placed on service members or to veterans' general patriotic reluctance to criticize the military. Second, in most other cases of military-site contamination, military secrecy and wartime control have clamped down on scientific and social discovery; this was the case with "atomic veterans" exposed to radiation testing (Wasserman and Solomon 1982), service members exposed to Agent Orange (Martini 2012) during the Vietnam War, and veterans who experienced Gulf War related illness (Brown et al. 2001). In those cases, organizing has been perceived as a threat to military policy and national security, and advocates have faced high levels of government silence and resistance. In contrast, PFAS are used in routine firefighting training and usage, falling into a general category of safety. Further, because AFFF foam is also used in civilian airports and in fire training sites for municipal firefighters, there is very broad general concern for safety issues with these chemicals, both in use and in storage.

As with many chemicals, scientists and the public are playing a catch-up game, as older chemicals are phased out and replaced with newer, but similar ones. While PFOA and PFOS are no longer produced by manufacturers in the USA, replacement compounds including short-chain PFAS and GenX are widely used in spite of growing concerns about widespread exposures and toxicity (Perez et al. 2013; Danish Ministry of the Environment 2015; Rae et al. 2015; Rosenmai et al. 2016; Sun et al. 2016; US EPA 2017). Corporations are protected from sharing names of chemicals in new products and mixtures, making it difficult or impossible for scientists to study the new replacements. Even the EPA, charged with evaluating new uses of chemicals, cannot gain access to chemical data (Richter et al. 2018).

There are many possible exposure pathways for PFAS, including direct exposure through occupational work, ingestion of drinking water, oral or dermal intake from consumer products containing PFAS, or ingestion of food grown on land treated with PFAS-contaminated biosolids. The EPA's Unregulated Contaminant Monitoring Rule (UCMR) found PFAS drinking water contamination affecting an estimated 15.1 million US residents in 27 states (US EPA 2018). The public is in constant contact with PFAS through everyday consumer products, such as fast food wrappers, though they are not generally aware of the extent of these exposures (Guo et al. 2009; Kotthoff et al. 2015; Liu et al. 2015;

Schaider et al. 2017). Research by the CDC's NHANES national biomonitoring program tested a nationally representative sample of US residents for 12 PFAS compounds from 1999 to 2014 and found four PFAS in the serum of nearly all the people tested (Centers for Disease Control and Prevention 2017, 2018). This is particularly concerning because these chemicals have demonstrated the potential for low-dose or hormone disrupting effects, and are persistent and bioaccumlative in the body and food chain (Post et al. 2012). These types of studies documenting widespread exposure (Environmental Working Group 2017) have brought PFAS to the attention of a new audience of environmental health scientists and involved the public, especially communities whose drinking water is contaminated with PFAS.

The combination of scientific and social discovery has had many impacts. In 2006, following pressure by regulators, scientists, and the national non-profit the Environmental Working Group, eight major PFAS manufacturers developed a voluntary PFOA Stewardship Program with the EPA to reduce long-chain PFAS emissions to all media and eliminate their use from products over the next decade (US EPA 2006). In 2009, the EPA developed Provisional Health Advisory levels for both PFOA and PFOS in drinking water (US EPA 2009). These levels were subsequently lowered in 2016 with a combined PFOA+PFOS health advisory level of 70 ppt (parts per trillion) (US EPA 2016a, 2016b). Some states have set advisory levels even lower than the EPA level, and New Jersey and Michigan even have made regulatory levels that are enforceable by law (Interstate Technology Regulatory Council 2018). States are beginning to look beyond PFOA and PFOS to other PFAS, conducting additional water testing, placing restrictions on the emissions of local industries after discoveries of local contamination, and developing drinking water guidelines for additional PFAS (New Jersey Drinking Water Quality Institute 2015; Hagerty 2018). Current and former military sites are installing carbon-activated filtration systems and/or providing alternative water sources. Following an appropriation in the omnibus 2018 Defense Authorization Bill, the Agency for Toxic Substances and Disease Registry, a part of the Centers for Disease Control and Prevention, will conduct a nationwide study of PFAS health effects.

The field of stakeholders working on PFAS is broad, and includes regulatory and academic scientists; industry advocates; regulatory agencies; military scientists and policy makers; legislators at the state and federal levels; residents of impacted communities; and community and social movement groups at the local, state, regional, national, and international levels. The PFAS movement has experienced a major shift, from targeted advocacy led by professional scientists and litigators to a grassroots effort in dozens of communities that is well networked at the national level (https://pfasproject.net/). The PFAS social movement extends from the local level, with individual activists and concerned residents advocating for biomonitoring, water testing, site clean-up, or delivery of uncontaminated water, to national non-profits that work on PFAS policy and other environmental and health-related issues. Contamination in Hoosick Falls, New York from a plastics manufacturing site is a good example of the grassroots movement happening nationwide around PFAS contamination. When PFOA municipal water contamination was discovered by a local resident in 2015, residents established a community activist group that advocated for a water testing study and ultimately led to the designation of Hoosick Falls as a state Superfund site. After learning of the contamination in Hoosick Falls, concerned residents in nearby North Bennington, Vermont began testing their drinking water for PFOA. Academics and students at Bennington College offered a course on PFAS that was open to all community members. Through these classes, citizens were educated about the health effects of PFOA and were able to amplify their local concerns and demands for safer water. A transdisciplinary team of faculty collaborated with local residents on two National Science Foundation grants to organize the class and fund the water testing.

Other community groups have also used science for their social movement activism, often working in collaboration with academics and supportive regulators. For example, Testing for Pease formed after residents learned that the drinking water supplying the Pease Tradeport, an industrial park on the site of the former Pease Air Force Base in Portsmouth, New Hampshire, was contaminated with high levels of PFAS from AFFFs. Testing for Pease is one of the best organized and most sophisticated of the community groups dealing with PFAS, and is involved with PFAS-related advocacy at the local, state, and national level. They pushed the New Hampshire Health Department for blood testing, organized residents, and helped other communities learn how to deal with PFAS contamination. In 2018, their co-leader Andrea Amico was one of only two representatives of contaminated communities invited to a national EPA summit on PFAS research and policy. Testing for Pease has written several research proposals with academics that will fund transdisciplinary CBPR projects to examine PFAS effects on children's responses to vaccines, and to test water to learn what chemicals are not being removed from common filtration systems. Extensive community organizing is occurring throughout the USA, with a national coalition of groups led by Testing for Pease and Toxics Action Center.

Conclusion

We have shown that toxic trespass is widespread, with all people subject to contamination by industrial products and their waste stream, as well as many household products. The combination of social and scientific discovery has accelerated in recent years, enabling the creation of many social movement organizations and pushing for more protective government regulation and corporate reform. This movement continues to flourish even as it meets resistance in the Trump era.

The most complete examinations of contamination causes, impacts, and resolutions are done by transdisciplinary teams with a community-engaged approach. Our team's experience of this is guided by a framework centered in science-motivated and engaged social change. In our engaged environmental sociology, not all aspects of our project strictly conform to the principles of CBPR, in that not all our activities involve solely working with specific communities, and community members are not involved in all stages of our research process; however, we would argue that our research is always community engaged and oriented toward a dialogue with impacted publics.

Environmental sociology grew up in a milieu in which activism and scholarship have been commonly combined. We see increasing numbers of physical and life scientists now doing what many social scientists have done, and consider this a beacon for future efforts. Three recent large grants have provided strong support for academic–community collaborations that have a strong public policy approach, in addition to the scientific research. An $8 million Superfund Research Program (Sources, Transport, Exposure and Effects of PFASs; STEEP) Center established in 2017 at the University of Rhode Island brings together scientists from that university, Harvard, and Silent Spring Institute with communities on Cape Cod in a multi-project center with a strong Community Engagement Core, working to avert the human and environmental health impacts of PFAS exposure and disseminate lessons learned to help avoid similar contamination problems in the future. The PFAS Project team at Northeastern, in collaboration with Silent Spring Institute environmental chemist Laurel Schaider (who is also part of the above-mentioned STEEP Center) and Michigan State University epidemiologist Courtney Carignan, received in September 2018 a $2.6 million grant, in partnership with community groups Testing for Pease, Toxics Action Center, and Massachusetts Breast Cancer Coalition. That project will study how PFAS can lead to decreased immune response to vaccines in children; document the experiences of affected communities by conducting in-depth interviews and ethnographic research; conduct water testing; and create the "PFAS Exchange"

– an online resource center for the public as well as medical professionals. The website will include a variety of educational materials, web-based tools to help residents visualize and interpret their blood test results, and resources for connecting affected communities. Also in September 2018, the PFAS Project received a $500,000 grant from the National Science Foundation to study PFAS activism across the United States, using its unique Contamination Site Database. That project also includes Silent Spring Institute, Toxics Action Center, and Testing for Pease, and will also conduct water testing. Finally, all the above parties worked with community groups and scientists to organize two National PFAS Conferences in 2017 and 2019 that brought together the whole range of players dealing with PFAS to learn from impacted communities and hear the latest updates in PFAS science and regulation.

The PFAS Project's website (pfasproject.com) posts daily the many news stories of continuing and newly forming community groups that are pushing for action on PFAS, ranging from local and state pressure to federal pressure that has resulted in Congressional funding for major research. We are fortunate to be both observing and studying, as well as helping to shape, an exciting energy involving this class of chemicals in all of their manifestations.

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