Earth 2020

An Insider's Guide to a Rapidly Changing Planet

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The Global Chemical Experiment

Elsie Sunderland and Charlotte C. Wagner

Since antiquity, humans have mined toxic elements such as mercury (Hg) and lead (Pb) from Earth's crust. The ancient Romans used Pb for their plumbing and kitchenware, while early Chinese and Egyptian civilizations colored their clothing and artwork with the brilliant red pigment of the Hg-enriched mineral, cinnabar. Paracelsus, the sixteenth-century physician and forefather of the field of toxicology, was an advocate for treating syphilis with mercury vapor rooms. Several hundred years later, nineteenth-century hat makers (the so-called mad-hatters) in Europe and North America inhaled acutely toxic levels of elemental mercury during the felting process. Today, fifty years after the first Earth Day in 1970, exposure to chemical toxicants has reached a planetary scale — a global chemical experiment in which we are all unwitting participants.

As the human population has grown exponentially over the past century, there has been an increased reliance on Pb, copper (Cu), zinc (Zn), and other heavy metals as 'technological nutrients' fueling modern industry.[1] In addition, almost 100,000 synthetic organic chemicals have been developed for everyday domestic and commercial use, in pursuit of 'better living through chemistry',[2] compliments of DowDuPont (the merger company of the Dow Chemical Company and DuPont, commonly still referred to as DuPont) and other major conglomerates. Synthetic fertilizers and pesticides have enabled the Green Revolution,[3] thereby avoiding the Malthusian population time bomb. At the same time, we are now undergoing a materials revolution, where the objects of the past, designed

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for a single purpose (think a desk, or book), are being replaced by 'smart materials' with multi-functionality. This revolution has led to spectacular combinations of the elements from across the periodic table into modern materials and gadgets, with capabilities well beyond what was imaginable even a generation ago. As a result, we are now faced with tens of thousands of chemicals used in our homes and in our everyday products. For the vast majority of these chemicals, we have only a limited understanding of how they will behave once released into the environment.

A major problem is that many synthetic chemicals are persistent in nature, meaning they do not readily break down following release into air, water or soils. This persistence allows the chemicals to accumulate in the environment, and to be transported long distances from their original sources if they are released to air or water. Heavy metals occur naturally on Earth, but their abundance in environments where they are likely to accumulate in organisms has increased dramatically due to human activities. For example, cumulative anthropogenic releases of Hg over the past 500 years have been fifteen times higher than those from natural sources such as volcanoes. Once released to the environment, chemical contaminants can be transformed into forms that are readily taken up by living organisms, resulting in a process of biomagnification up the food chain, with increasing concentrations encountered in each successive step from prey to predator. Apex predators, including humans, sit at the top of the trophic pyramid, and are thus most vulnerable to persistent and bioaccumulative chemicals. As a result, the blood of nearly every mammal on the planet, from humans in Madagascar to polar bears in the Arctic, now contains a cocktail of global toxicants such as chlorinated, brominated and fluorinated synthetic organic compounds, Hg and Pb, among other substances.

By the time of the first Earth Day in 1970, chemical contamination of air, water and soil was well established. High profile cases, including dichlorodiphenyltrichloroethane (DDT) and other pesticides, along with wide-spread industrial pollution of various lakes and waters, prompted the formation of the US Environmental Protection Agency (US EPA) in 1970, and milestone legislations such as the Clean Water Act[4] and the Clean Air Act (US).[5] Yet, despite growing awareness of the threat of pesticides and other toxic chemicals, significant human impacts on natural ecosystems and human health continued. The deadliest example of such impact was the gas leak and explosion that occurred in December 1984 at the Union Carbide pesticide plant in Bhopal, India. Over 500,000 people were exposed to methyl isocyanate gas, and more than 2,000 eventually died from acute symptoms. The ground hugging deadly fog was a powerful image of the toxic effect of pesticides, but even more dire was the contamination of soils and groundwater, which led to an estimated 15,000–20,000 premature deaths in the subsequent two decades, painting a dark picture of the long-term effects of chemical exposures.

Awareness of the health risks associated with exposure to environmental contaminants among the general public has typically depended on acute exposures or mass poisonings resulting in visible health effects or death. In their landmark 2006 review paper in *The Lancet* medical journal, Drs. Philippe Grandjean and Philip Landrigan eloquently describe a predictable path for society's understanding of the health costs of industrial chemical exposures.[6] Acute poisoning events spark public interest and support for expensive research on a few select compounds. After several decades of research, a weight of evidence is established showing the 'silent pandemic' of health effects associated with chronic, low level exposures to globally-ubiquitous pollutants. Perhaps the best-known examples of this are Pb and Hg.

More than a century ago, poisoning of young children by peeling flakes of Pb-based paints was documented in Australia, and this was followed by repeated cases in Europe and North America. During the 1970s and 1980s, while we were happily combusting and releasing huge quantities of Pb as tetraethyl lead in gasoline, Bruce Lamphear, now at Simon Fraser University in Canada, conducted pioneering research linking children's blood Pb levels to IQ deficits.[7] Based on Lamphear's work and that of others, the level of blood lead considered 'safe' by the US Center for Disease Control (CDC) dropped from 60 mg/dL in 1960 to <5 mg/dL in 2012. Researchers now believe that all levels of Pb exposure may be associated with neurodevelopmental deficits, and problems of lead contamination still remain. In 2014, for example, high Pb levels were reported in the drinking water of Flint, Michigan due to a shift in their water source to the Detroit River, and the leaching of Pb out of acidic supply pipes.

Mercury contamination, like Pb, also gained significant public attention during the second half of the twentieth century, in response to several high-profile public health disasters. In the late 1950s, industrial discharges of an organic form of mercury into Minamata Bay, Japan led to the now infamous cases of Minamata disease, an acute form of Hg poisoning that results in tremors, impaired vision, memory loss, hair loss, birth defects and death. In the 1970s, an international food aid shipment to Iraq included grain seeds coated with an organomercury compound. The starving population consumed the grain in bread rather than planting the seeds, as intended, leading to severe mercury poisoning across the population. Today, many members of the public and the media incorrectly associate relatively low-level methylmercury exposure through consumption of fish with risks of Minamata disease. However, like Pb, there appears to be no lower threshold for chronic low-level methylmercury exposure and neurodevelopmental delays.

An emerging class of fluorinated organic compounds, poly- and perfluoroalkyl substances (PFAS), are this generation's organochlorine pesticides. These compounds have been used since the 1960s, mainly for their surfactant properties in various products ranging from Teflon pans, outdoor gear and food packaging, to aqueous fire-fighting foams. They are known as '**F**orever-**C**hemicals' because they contain a fluorine (F)–carbon (C) bond that is not known to degrade under natural conditions. Like Pb and Hg, awareness of the health risks associated with these chemicals was ignited by the public outcry of communities located next to manufacturing facilities with contaminated water, soils and food. High levels of exposure to PFAS have been linked to wide range of health issues, from cancer to thyroid disease.[8] At low exposure levels, these compounds have been associated with the most potent immune-toxic response ever documented for a synthetic chemical present in the environment. In response to these acute health risks, the US EPA lowered provisional advisories for drinking water PFAS concentrations from 400 ng/L to 70 ng/L in 2016. Many states in the US are now contemplating limits ranging from 5–20 ng/L.

Over the past several decades, we have learned that exposures to a wide range of anthropogenic chemicals are associated with diverse deleterious health outcomes. There are critical windows of vulnerability to chemical exposure — such as the developing fetus during the third trimester of pregnancy, when the brain is developing most rapidly, and during the first several years of life when the body's immune programming is taking place. In their landmark 1996 book, *Our Stolen Future*, Theo Colburn, Dianne Dumanoski and John Peterson Myers brought together large amounts of scientific data linking declining human fertility with a rise in exposure levels to estrogen-like structures present in many common synthetic chemicals.[9] They put forward the so-called 'endocrine disruptor' hypothesis, arguing that hormone-like synthetic compounds were taking a heavy toll on humans and wildlife, interfering with the organism's natural chemical signaling pathways. We now also know that exposure to various forms of arsenic (As), PFAS and polychlorinated biphenyls (PCBs) is associated with impaired immune health, while PFAS and other synthetic organic compounds impair fat metabolism, potentially contributing to a growing global obesity epidemic. Linda Birnbaum, the recently retired Director of the US National Institute of Environmental Health Sciences, points out that the environment is suspected to be the primary cause for recent increases in the incidence of many chronic diseases in the US population, because shifts in lifestyle, diet and behavior patterns have not shown parallel trends.[10]

A major problem in regulating the production and release of toxicants into the environment has been the reactionary rather than proactive approaches to management that are still pervasive today. This began with the public outrage following Rachel Carson's description of the impacts of indiscriminate pesticide use in *Silent Spring* (1962),[11] which catalyzed the formation of the US EPA in 1970 under President Richard Nixon. Yet, despite its mission to 'protect human health and the environment',[12] and an innovative mandate to study the health effects of new chemicals, progress by the EPA has been slow. In 1976, the first iteration of the Toxic Substances Control Act grandfathered 60,000 chemicals already in use, effectively considering them as safe and exempting them from further scrutiny. This law was finally revisited by the US Congress in 2016, with the Frank R. Lautenberg Chemical Safety for the 21st Century Act.[13] Similarly, the Clean Air Act (US) and the Clean Water Act, both seen as milestone achievements of environment legislation, have only focused on regulating a handful of specific toxicants. Only eighty-three contaminants are regulated in drinking water as part of the Safe Drinking Water Act and no new chemicals have been added since the law was promulgated in 1974. And sometimes, hard-won progress has been reversed. For example, long-standing US regulations on the emission of Hg from coal-fired utilities (the largest remaining source in the country) were rolled back by President Trump in 2019. If we are unable to regulate toxicants like Hg, well-established to pose public health risks with societal costs in the many billions of dollars, effective regulation for other chemicals seems nearly impossible.

On the international front, chemicals management has been similarly reactive in nature. Negotiations toward the establishment of the Stockholm Convention on Persistent Organic Pollutants (POPs) began in 2001, and the global treaty entered into force in 2004 with 128 signatory nations. However, only twelve POPs were initially included in the agreement (the 'dirty dozen'), and only nine were added after the first update in 2009. The global treaty on Hg (Minamata Convention on Mercury) entered into force in 2017, but progress has been slow in establishing international agreement on how emissions reductions will be accomplished. Although these agreements represent major accomplishments in international policy, their utility for reducing ubiquitous exposures to toxic substances has so far been limited.

To address this problem, the European Union put forward an innovative approach to chemical management in 2007 known as REACH: Registration, Evaluation, Authorization and Restriction of Chemicals.[14] This regulatory framework places the burden of proof for harm associated with chemical substances on manufacturers, and advocates for a more precautionary approach than used in North America. However, enforcement has proven to be challenging, and the general consensus among experts is that the ambitions of the regulations have not matched their accomplishments to date.

As we look to the future, advocacy on behalf of communities and public outrage remain the most effective and timely method for enacting changes in chemical use and releases. As a graduate student in the late 1970s, Arlene Blum, the famous mountaineer and founder of the Green Science Policy Institute, reported high levels of carcinogenic brominated flame retardants in children who wore treated pajamas, leading to the first regulations for these chemicals. More recently, public attention has been mobilized around the potential health impacts of PFAS, which have contaminated the drinking water of hundreds of communities across the US. Work by Rob Bilott, an attorney who litigated DuPont on behalf of the community in Parkersburg, West Virginia, which was affected by the company's pollution of that area, has made these odd-sounding chemicals a household concern across the country. His work was the subject of a major 2019 Hollywood film, *Dark Waters*, directed by Todd Haynes. Under increasing public pressure, states and the Federal US Government are now scrambling to respond with new regulations for drinking water, food contact materials and waste products that are used for biosolids. The main global manufacturer of PFAS in North America, 3M, voluntarily discontinued manufacturing the parent chemical to one of the most abundant PFAS found in the environment and humans between 2000–2002. This led to large and rapid declines in the concentrations of this chemical in the environment and human blood throughout North America and Europe, illustrating the benefits of coordinated decisive action on environmental releases. Unfortunately, however, PFAS have become the latest example of chemical whack-a-mole; one compound is phased out, only to be quickly replaced by another whose environmental properties and health consequences are largely unknown. The same game of chemical whack-a-mole has been played for different brominated flame retardants and plasticizers such as bisphenol-A in water bottles and other products. Each banned chemical is replaced by new compound that is initially assumed to be safe, but later discovered to be a regrettable substitution and problematic in its own right.

Addressing the global chemical experiment requires a new kind of thinking about environmental issues. First, current education and research still emphasize single disciplines. This isolates the chemical engineers responsible for creating new and better materials for society from the environmental toxicologist and health scientists who could screen for potentially deleterious effects prior to industrial use and widespread environmental release. Most chemical engineers are not currently trained in basic environmental science and risk assessment, yet this could be easily incorporated into standard teaching for undergraduates. Tools for screening potentially adverse impacts of new chemicals on human and ecological health have already been developed by various regulatory agencies, yet their full potential has yet to be realized. For example, the US EPA has developed a computational toxicology screening tool known as 'ToxCast' that uses high throughput screening assays to understand potentially adverse impacts of exposure for living organisms.[15] Use of this and other emerging screening tools would be simple and inexpensive prior to widespread use of chemicals in commerce.

The path toward sustainability in chemicals management is achievable. Tom Graedel from Yale's School of Forestry has shown that tracking the use of chemicals from manufacturing to disposal can improve conservation and optimize material flows.[16] Similarly, the movement towards a 'circular economy' has demonstrated to manufacturers that eliminating chemical releases through reuse rather than disposal can be profitable, while also providing good public relations. Positive notes for the future include the examples for Hg, Pb and PFAS, among others, where society has taken decisive action toward chemical management, and concentrations in humans and wildlife have dropped significantly shortly thereafter. Engineering innovations have produced emission control and waste treatment technologies that can virtually eliminate many of the chemicals of concern from our power plants and wastewater effluents. However, investment of societal resources in implementing such technologies remains a challenge that must be addressed to end our global chemical experiment.

Endnotes

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2 'Better living through chemistry' is a variant of the famous DuPont advertising slogan, which was used by DuPont (a now defunct American conglomerate) in various forms from 1935 through to 1999.

3 See 'Land' by Navin Ramankutty and Hannah Wittman in this volume.

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