Measuring historical pollution: natural history collections as tools for public health and environmental justice research

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ABSTRACT

Background

Through the industrial era, environmental pollution has been unevenly distributed in the environment, disproportionately impacting disenfranchised communities. The distribution of pollution is thus a question of environmental justice and public health that requires policy solutions. However, we lack robust quantitative data on pollutants for many locations and time periods because environmental monitoring is largely reactive—i.e., pollutants are monitored only after they are recognized as harmful and circulating in the environment at elevated levels. Without comprehensive historical pollution data, it is difficult to understand the full, intergenerational determinants and consequences of pollutants on environmental and human health. Here, we promote the use of biological specimens in natural history collections as an underutilized source of quantitative pollution data for tracking environmental change over nearly two centuries and for informing justice-centered policy solutions.

Objectives

First, we discuss the need for quantitative pollution data in environmental research and its implications for public health and policy. We then examine the capacity of biological specimens to serve as tools for tracking environmental pollutants through space and time. We then present a framework for how pollution datasets from specimens can be paired with spatially and temporally matched human health datasets to inform and evaluate public policy. Finally, we identify challenges and research directions associated with the use of quantitative pollution datasets.

Discussion

Biological specimens present a unique opportunity to fill critical gaps in the environmental record—and to generate historical data for emerging pollutants—to engage public health and policy questions that we have previously lacked data to address. This work demands diverse expertise and partnerships across the sciences, and between researchers and communities affected by pollution, to connect data generated from specimens with urgent questions about environmental health and justice, and to find solutions to some of the most pressing environmental challenges of the twenty-first century.

MAIN TEXT

A key feature of environmental pollution is that it is unevenly distributed across space and time, often with marginalized communities experiencing higher rates of harmful exposure (United Church of Christ Commission for Racial Justice 1987, Bullard 2008, Mohai et al. 2009, Hill 2020, Goldsmith and Bell 2021, Tessum et al. 2021). How environmental pollution is (and has been) distributed—and its unequal impacts on different human populations—is thus a question tied to issues of historical inequality, environmental racism, environmental justice, and public health and policy more broadly (Mohai et al. 2009). The ability to link pollution exposures to public health and policy decisions, however, is constrained by a lack of quantitative spatial and temporal data on pollution concentrations in the environment (Institute of Medicine 1999, Payne-Sturges and Gee 2006, Mohai et al. 2009, Wang et al. 2019).

Combining spatial and temporal data is necessary for understanding the uneven impacts of past and present pollution. For example, Colmer et al. (2020) show that significant disparities in air pollution exposure have persisted across communities in the continental U.S. over the last four decades, even as overall concentrations of air pollution have dropped across this period. While this study used one of the most comprehensive pollution datasets to date, including 36 years of air pollution data, this time frame does not reflect the full scope of many pollutants' impacts, circulation, and persistence in the environment. Many health outcomes associated with pollution manifest later in life as a product of long-term exposure. Thus, to fully understand the links between human health and pollution requires long-term data on when and where pollutants occur. Without robust spatial and temporal data of historical pollution levels it remains difficult to understand how pollution loads have changed (and are changing) in the environment, which is consequential for developing policies that effectively redress past harm and prevent widening health disparities (Arcaya and Figueroa 2017). Here, we propose that the missing environmental data necessary for understanding the impacts and extent of pollution, as well as generating historical data for emerging pollutants, may come from an underutilized data source: biological specimens in natural history collections.

Over the last 200 years, there have been significant public and private efforts to collect plants and animals from around the world for biological research. As a result, hundreds of millions of specimens are now stored in natural history collections, where they are primarily used to catalogue the world's biodiversity and understand its origins (National Academies of Sciences, Engineering, and Medicine 2021). Incidentally, these specimens also function as *time capsules*, preserving pieces of the environments they inhabited (e.g., Figure 1). These specimens offer researchers material records of past environments that can be used to quantify spatiotemporal changes in environmental pollution. For example, in a textbook example that led to key environmental legislation in the U.S. (and a focus of Rachel Carson's book *Silent Spring*), researchers analyzed a time series of bird eggs from natural history collections, uncovering how the insecticide DDT was responsible for eggshell thinning and declines in bird populations in the U.S. and U.K. (Ratcliffe 1967, Hickey and Andersen 1968). Bird and fish specimens have also been used to track the rise of heavy metals and microplastics in terrestrial and aquatic environments (e.g. Vo et al. 2011, Bond et al. 2015, Hou et al. 2021, Ilechukwu et al. 2023), and bird specimens have been used to reconstruct over a century of atmospheric pollution across the U.S. Industrial Belt (Figure 1, DuBay and Fuldner 2017). Given the sampling abundance, historical breadth, and spatially explicit nature of specimen collections, they can be used to understand pollution concentrations in the environment from decades before systematic efforts to monitor the environment were established. Furthermore, the groundwork for using specimens to link pollution to human health has already been done, with decades of research demonstrating that the levels of over a hundred pollutants can be reliably estimated from specimens (Table S1), including some of the most concerning pollutants for human health. This capacity of specimens to be used as indicators of environmental health is implicit in GeoHealth and One Health frameworks that acknowledge how geography, plant and animal health, and public health are closely intertwined (American Geophysical Union, n.d.; Center for Disease Control and Prevention, n.d.).

Here, we suggest that natural history collections have unique potential as time capsules to inform human health, public policy, and environmental justice, providing opportunities to reconstruct past environments and fill critical gaps in the environmental sampling record. With this perspective, we first discuss the need for quantitative spatial and temporal pollution data. We situate this discussion within a justice-oriented framework of environmental health, but the need for quantitative historical pollution data is broadly applicable to public health and policy. Second, we examine the robust history of using specimens to track and quantify environmental pollution, which falls within the areas of ecotoxicology and bioindicator research. In this section, we argue that bioindicator research has always been rooted in human health concerns, but few studies to date have realized their full potential in linking pollution loads and exposure risk to community-level health impacts and policy. Lastly, we present a framework for how natural history specimens can contribute to a spatial and temporal understanding of past pollution—and for emerging pollutants—that can be linked to spatially and temporally matched human datasets to inform public health and policy decision-making. This work builds toward a multidisciplinary approach that spans the natural, physical, and social sciences, and requires collaboration between research communities and the public, to find creative and collective solutions to some of our most pressing environmental and health challenges.

Figure 1: An example of how specimens function as *time capsules*, preserving pieces of the environments they inhabited (from DuBay and Fuldner [2017]). The figure compares two Field Sparrows (*Spizella pusilla*) collected within the U.S. Industrial Belt, one from 1906 and one from 1996. The specimen from 1906 is covered in black carbon particulate from coal burning in the region at that time. The lower panels show SEM micrographs of belly feathers plucked from the specimens in the upper panel. The SEM micrographs of the Field Sparrow from 1906 show aggregates of black carbon sphericals, while the feather from the 1996 specimen lacks black carbon deposition.

The consequences of incomplete data on historical pollution

Understanding pollution in the environment is critical for understanding human health because pollution is one of the most acute forces by which environmental disparities manifest in peoples' lives. In 2003, the term "One Health" was coined at a meeting hosted by the Wildlife Conservation Society to capture the notion that, "the health of people is closely connected to the health of animals and our shared environment" (Center for Disease Control and Prevention, n.d.). To fully understand the connections between human health and the environment, we must also understand the sociopolitical and economic systems that shape our environments and maintain pollution in the first place (Murphy 2008, Liboiron 2021). In acknowledging these connections (referred to by sociologists as the *political economy of the environment* [Rudel et al. 2011]), we can begin to understand human health as influenced by social structures (i.e., the social determinants of health) that shape where, when, and to what extent (or in what concentrations) pollution occurs and the resulting differences in exposure between populations. One of the clearest examples of these connections is the impact of U.S. infrastructure and housing policy that has enforced decades of residential placement, segregation, and redlining across the U.S., concentrating marginalized populations in environmentally degraded and polluted areas (Singer 2011, Taylor 2014, Collins et al. 2015, Castellón 2021, Lane et al. 2022). Another example lies in the polluting industries themselves, which often follow a 'path of least resistance', resulting in the placement of polluting facilities in, or adjacent to, communities that have been politically and economically disenfranchised (Taylor 2014, Mohai and Saha 2015, Begum et al. 2022). In the U.S., policies and industrial siting decisions disproportionately impact Black, Indigenous and Latinx communities, poorer communities, LGBTQ+ communities, populations experiencing greater incidence of mental health illness, and people with disabilities (Payne-Sturges and Gee 2006, Taylor 2014, Liévanos 2018, Tessum et al. 2019, Goldsmith and Bell 2021, Tessum et al. 2021, Chakraborty 2022). These effects also compound at the intersections of different populations and identities (Homan et al. 2021). Within these subpopulations there are higher incidences of cardiovascular disease, cancer, respiratory illness (such as asthma), cognitive disorders, and preterm birth, among others adverse health impacts (Payne-Sturges and Gee 2006, Culhane and Goldenberg 2011, Collins et al. 2017). Data on the environmental conditions that communities have experienced in the context of social structures are thus necessary for informing efforts to redress past and ongoing health inequities and for mitigating future inequity.

A key shortcoming of efforts to measure pollutants is that environmental monitoring generally begins only after pollutants have reached critical levels in the environment and have resulted in observable effects on human or other animal populations. This time lag in monitoring means that we often lack sufficient retrospective pollution data, which in turn skews our historical understanding of the buildup and life cycle of pollutants in the environment. For example, in 1955 the U.S. passed its first federal air pollution legislation, the Air Pollution Control Act, in response to decades of research and activism to reduce atmospheric black carbon pollution (also known as soot) from coal burning (Stradling 1999). The Air Pollution Control Act established the first national network to monitor air quality, but black carbon pollution in the U.S. had already peaked decades earlier, and by 1955, levels of black carbon pollution were declining (Stradling 1999, Bond et al. 2007, DuBay and Fuldner 2017). Environmental monitoring—as it has been deployed—is thus characteristically reactive, resulting in an incomplete record of pollutants in the environment.

While some spatially- and temporally-explicit datasets currently exist that have been used to understand the origins and impacts of pollutants (e.g. Colmer et al. 2020), current pollution datasets often insufficiently capture: (1) the time scales at which pollutants impact, circulate in, and persist in the environment, (2) the joint spatial and temporal heterogeneity of pollution, and (3) the co-production and co-distribution of multiple pollutants. A lack of spatially and temporally paired data limits our ability to answer longstanding and emerging questions that have been identified by environmental health researchers, some of which we highlight in Table 1.

Table 1. Critical questions that have been identified by environmental health and justice researchers. The references provide examples of where each question has been identified.

Critical questions about environment health and justice	References
Who is (and has been) exposed to which pollutants?	Brulle and Pellow 2006 Mohai et al. 2009
What are the transgenerational impacts of exposure on health outcomes and communities?	Fitzgerald et al. 1998, Anway et al. 2005 Schmidt 2013, Hoke and McDade 2014 Lombó et al. 2015, Bové et al. 2019 Shukla et al. 2019
How do pollutants co-vary across the environment, and what are the impacts of multiple stressors on human health?	Morello-Frosch and Shenassa 2006, US EPA 2007, Dominici et al. 2010 Billionnet et al. 2012, Levy et al. 2014 Rodgers et al. 2020
What are the potential pathways of human exposure (e.g., exposure from the outdoor vs. built environment)?	Wallace 1991, Rosenbaum et al. 2011 Li et al. 2021
How will future land use and environmental change influence the distribution and accumulation of pollutants?	Tang et al. 2005, Schilling et al. 2008
How do changes in biodiversity and land-use impact the flow of pollutants through food webs and ecosystems?	Maiti and Chowdhury 2013 Lepak et al. 2019, Nilsen et al. 2019
What are the cumulative effects of multiple exposures and chronic low-level exposure?	Di et al. 2017, Nilsen et al. 2019
What are the consequences and efficacy of past policy to reduce exposure to pollutants?	Crabb and Leroy 2012

Filling spatial and temporal gaps in the environmental record will aid in efforts to tackle the questions in Table 1, and many more. Natural history specimens—in their capacity to track environmental change—offer data and historical perspective that can work in service of health equity and environmental justice.

Natural history specimens and their use as bioindicators

Over the last two centuries, millions of zoological and botanical specimens have been collected throughout much of the world (Figure 2 and 3) (National Academies of Sciences, Engineering, and Medicine 2021). These specimens are housed across hundreds of natural history collections globally where they are available as a source of data. The origins of many of these collections, like those in the U.S. and Europe, are inextricably tied to extractive and imperialistic practices of Western science, which sever specimens from the environments they once inhabited (MacKenzie 1990; Quintero Toro 2012; DuBay, Palmer Droguett, Piland. 2020; Kilbourne 2020). We propose, however, that using specimens to understand past environments can help reconnect specimens to the places from which they came to address place-based environmental challenges.

With each specimen, information is recorded about when and where it was collected—dates are often documented to the level of calendar day and year, and locations are usually documented to the level of county (Figure 4), township, etc., but can be as specific as cross-streets or georeferenced latitudes and longitudes (Figures 2 and 3B). In addition, numerous types of tissues have been preserved for posterity—dried study specimens of birds, mammals, insects, and plants; frozen tissues; and wet specimens (preserved in fluid) of fishes, birds, mollusks, reptiles, and amphibians (Webster 2017). Although spatial and temporal gaps in sampling exist, the breadth of sampling spans urban-rural gradients, land cover types, land-use gradients, and geopolitical boundaries. Time-series of specimens can thus be analyzed to address questions across various spatial and temporal scales of interest, for example, at local, regional, or continental scales, and across seasons, decades, or centuries of environmental change. Different spatial scales of potential interest can be seen in Figures 2-4.

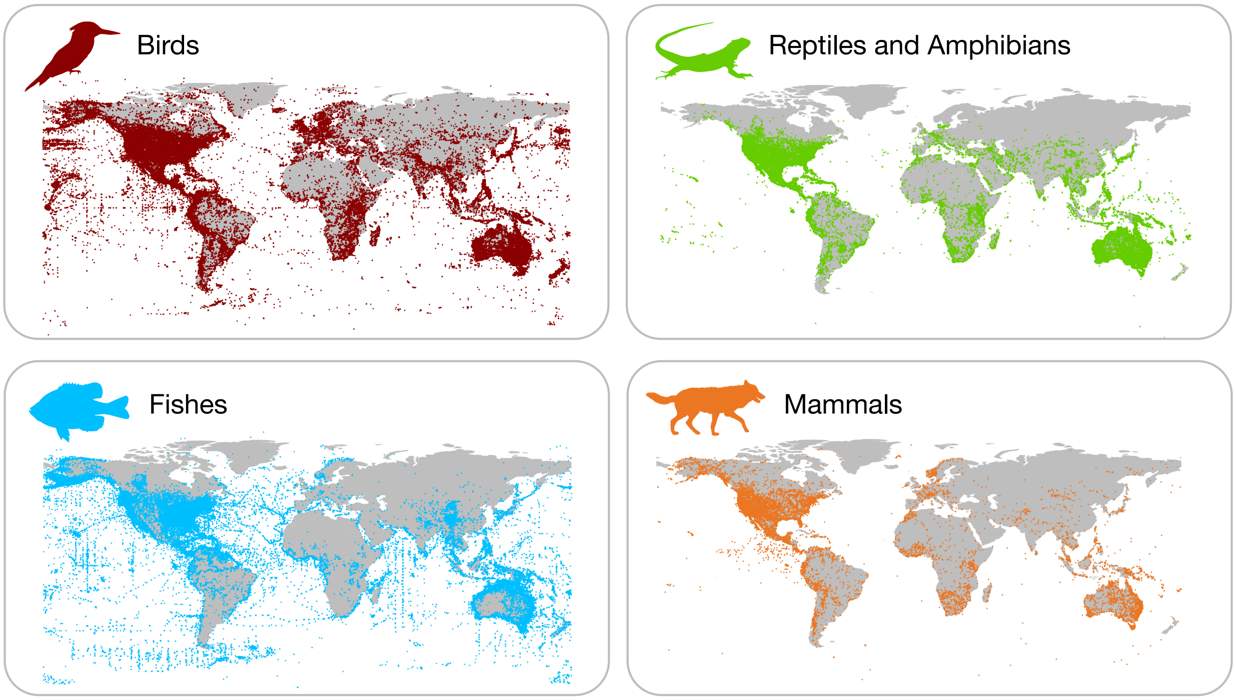

Figure 2: Global maps showing the extent of vertebrate specimens from over 125 natural history collections. Each point represents an individual georeferenced specimen, from 1850 to present. Sample sizes: Birds (n = 2,074,502), Reptiles and Amphibians (n = 296,720), Fishes (n = 502,430), and Mammals (n = 68,227). Maps were compiled from specimen records on Vertnet.org, an aggregate specimen database of global natural history collections.

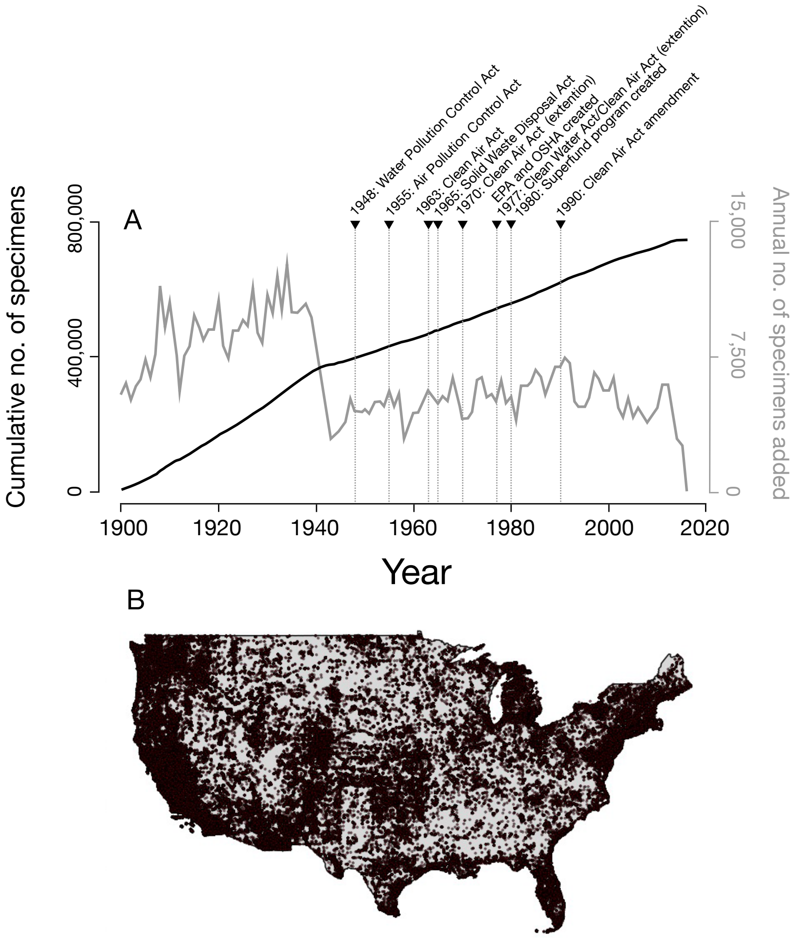

Figure 3: Vertebrate specimens from the continental U.S. from 1900 to 2016, compiled from Vertnet.org. (A) Specimen acquisition through time with a timeline of key environmental legislation in the U.S. Black line shows cumulative specimens in collections through time. Gray line shows the number of specimens entering collections each year. (B) Specimen map. Each point represents a single specimen. The sharp drop in specimens in the last five years of the time series is likely artificial, reflecting a time lag in new acquisitions being entered into museums databases.

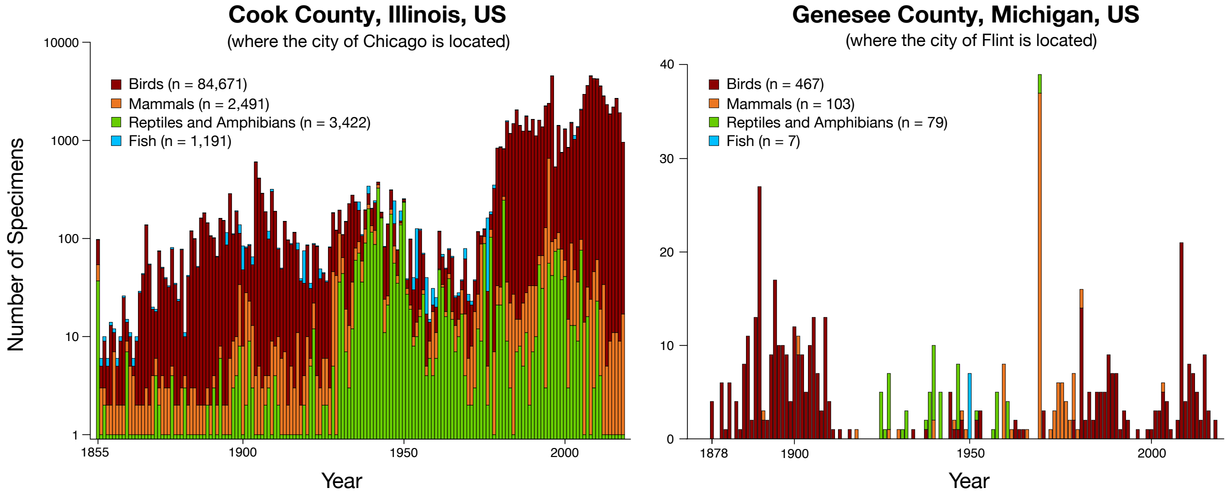

Figure 4: Examples of vertebrate specimen sample sizes through time from two U.S. counties with long histories of environmental contamination, Cook Co. and Genesee Co., which include the cities of Chicago and Flint, respectively, and their surrounding areas. These plots show the range of variation in historical sampling that exists in natural history collections at finer spatial scales. Plots were compiled from specimen records on Vertnet.org.

Since the 1960s, the potential for using plants and animals to understand environmental pollutants has been an active area of scientific research (e.g., Ratcliffe 1967, Hickey and Andersen 1968). For example, studies have examined how animals sequester and bioaccumulate pollutants from the environment in their tissues (feathers, hairs, bones, muscles, organs, exoskeletons, etc.) (relevant studies can be found in Table S1). In trees, tar spots and leaf/needle damage reflect exposure to air pollutants like sulfur dioxide and ozone (e.g. Oshima 1974, Bevan and Greernhalgh 1976). Bivalves in aquatic systems, like mussels, filter pollutants from the water column and sequester these pollutants in soft tissues, which have been measured to assess heavy metal contamination and pollutants from plastics like phthalates and polychlorinated biphenyls (PCBs) (e.g. Marigómez et al. 2013), and fish have been used to assess changes in microplastics in the environment (Hou et al. 2021). These examples highlight a small subset of studies that have documented how plants and animals capture pollutants from the environments they inhabit. These examples—and others mentioned throughout the text — also highlight the various ways in which organisms bioaccumulate pollutants. For example, black carbon particles accumulate superficially on an organism, such as on bird feathers, while heavy metals bioaccumulate in animal tissues, like bone. A non-exhaustive list of more than a hundred pollutants that have been assessed in most major plant and animal groups can be found in Table S1.

The motivation for much of this research on pollution levels in plant and animal tissues is largely predicated on the assumption that organisms are reliable bioindicators that can be used to better understand exposure and the broader impacts of pollutants on ecosystem health and human health. However, there is a gap between measuring pollutants in specimens and their use in public health research, in part because of the complex analyses required to relate specimen-based pollution data to human health outcomes. Two other reasons may also help explain why natural history specimens have been underutilized in environmental health research. First, most bioindicator studies assess either temporal dynamics alone (from a single location or a handful of locations through time), or spatial variation for a given point in time. That is, most research does not jointly assess spatial and temporal dynamics, which limits how this methodology can be used for questions of public health and policy given the spatial and temporal complexity of environmental pollution. Second, there are disciplinary silos that prevent useful exchanges and data integration. On one hand, the natural history museum community has access to specimens but has been predominantly invested in questions related to biodiversity (Webster 2017). On the other hand, public health, policy, and environmental justice communities are driving questions about human health and equity, but they may have less familiarity with, or access to, biological collections. A necessary first step in realizing the full potential of biological collections for public health is to find ways to connect disciplinary communities, which has significant potential for mutual enrichment, as exemplified in ongoing efforts to use natural history specimens to understand emerging pathogens and zoonotic diseases, and to track and monitor animal vectors of disease (for detailed accounts of this work see Cook et al. 2020, Colella et al. 2021, and Thompson et al. 2021).

Linking historical pollution data with public health and policy

The *time capsule* feature of natural history specimens makes them uniquely valuable for reconstructing the environmental record for pollutants of public health concern, as well as a key data source for understanding emerging pollutants in the future. By analyzing pollutants from a time series of specimens, there is significant potential to build spatially dynamic datasets of pollutants over long periods of time, which can be paired with spatially and temporally matched datasets of human health and demography, environmental policy, and more. In Box 1, we outline a potential workflow to illustrate these connections using lead pollution as an example.

Spatially- and temporally-explicit datasets would provide a foundation for quantitative assessment of salient questions, for example, about how pollution levels and exposure risk are moderated or exacerbated by policy choices and social contexts, or how exposure risk is associated with disparities in public health outcomes over time. Past and current pollution data could also be paired with demographic data to explore links between exposure risk and population density, race, income, and other factors to identify pollutants to which communities are at risk of being exposed. Pollution data from biological specimens can be used to inform environmental and land-use policy; they can also be used to estimate exposure risks in parental and grandparental generations to better understand the transgenerational impacts of exposure on human health. Furthermore, pollution data could be compared with mortality or morbidity data of various diseases to assess associations between exposure risk, health outcomes, and disease pathology. This is particularly relevant for diseases such as neurological disorders that manifest later in life and potentially result from long-term exposure to pollutants at low levels (Ritz and Yu 2021). For these diseases, we have lacked datasets of appropriate time scale to understand their pathologies, and temporal pollution maps could provide the key to better understanding the relationships between exposure and disease. Methodological models already exist for joining spatial and temporally matched dataset, for example, in linking air quality to health outcomes, like for asthma (Friedman et al. 2001) and COVID-19 mortality (Villeneuve and Goldberg 2020, Wu et al. 2020, Kerr et al. 2021). What we propose here is to extend these types of methods to robust, quantitative pollution datasets built using time series of natural history specimens.

Challenges and big questions moving forward

With quantitative pollution data, there are several public health and environmental challenges that we can begin to address with robust, spatially dynamic temporal data. Addressing these challenges will demand diverse expertise and creativity, opening up a transdisciplinary space for community-based research and engagement while bridging the natural, physical, and social sciences. Some of the challenges that robust pollution datasets will help clarify and contribute to include:

(1) *Understanding the transgenerational impacts of exposure and the impacts of long-term exposure, chronic low-level exposure, and time lags in exposure on health outcomes:* Understanding these impacts has been challenging not only because we

have lacked the necessary breadth of temporal data on exposure, but because of the time lags between exposure and the onset of health conditions. The temporal breadth of data from specimens (that spans multiple generations) is situated to tackle this exact challenge.

(2) *Disentangling cocktails of exposure and the associations between individual pollutants and public health outcomes:* Pollutants often co-vary through time and space, and individuals are exposed to multiple pollutants across their lifetime. These dynamics present major challenges for disentangling the impacts of distinct pollutants on health outcomes and establishing the origins of pollutants to hold polluters accountable. It will be important to develop temporal and spatial sampling schemes that allow researchers to delineate the respective and combined effects of multiple pollutants on public health outcomes, while being able to trace pollutants to their industrial origins. For example, chemical analyses were critical in linking General Motors to PCB waste that entered the Raquette and St. Lawrence Rivers to hold them legally accountable for remediation and damages (DeCaprio et al. 2005, Begum et al. 2022). The spatial and temporal breadth of natural history specimens makes them well suited to tackle these challenges by capturing the subtleties of how pollutants co-vary across the environment. Achieving this will bring us closer to moving from correlation to causality.

(3) *Calibrating historical levels of exposure and deposition with modern sample data:* We can assess trends of pollutant levels through time, but how does the pollutant level in an individual animal/specimen relate to the level being emitted and deposited in the environment? By pairing modern environmental pollution data with pollutant levels in specimens sampled at present day, we can calibrate pollution models to better estimate historical pollution levels in the environment. There is a lot that we can learn by understanding relative trends in historical pollution but having estimates of the actual concentrations/levels in the environment can help us tackle some of the other challenges mentioned here.

(4) *Understanding how pollutants move through the environment and biological systems:* Just because a plant or animal was exposed to a pollutant does not necessarily translate to human exposure. It will be important to understand how pollutants move through the environment and across trophic levels (i.e., food webs), while defining the pathways through which humans are exposed from the environment and understanding when and how human exposure is coupled or decoupled from non-human animal exposure—e.g., what is the extent of lead exposure coming from the external environment vs. the built environment, like from water pipes? This work will allow us to better understand how exposure relates to the outdoor environment vs. the built environment, while disentangling the two, and will help uncover possible routes of human exposure.

(5) *Understanding the role of organisms in filtering or concentrating pollutants in the environment:* To what extent are plants and animals providing an ecosystem service that benefits human health by removing pollutants from the environment? In contrast, how

are organisms concentrating and increasing pollutants locally by accumulating pollutants from one location and depositing them in another location (e.g., via movement coupled with death, excretion, molting, etc.)? Furthermore, how do these competing dynamics change through space and time and with biodiversity loss, land conversion, and habitat degradation? While a key feature of the framework presented here is that specimens can help us understand pollution dynamics through space and time, these data can also be used to understand the interactions between pollution, biodiversity, and exposure risks.

(6) *Understanding the mechanisms of accumulation, storage, and degradation of pollutants in organisms and biological samples*: While much research has shown that organisms bioaccumulate pollutants from their environments, it will be critical to better understand how this accumulation happens, and if/how pollutants degrade in natural history specimens over time. We expect, for example, that pollutants such as heavy metals and persistent organic pollutants (like PCBs) remain at stable levels in specimens through time in collections, but information about the "life cycle" of a pollutant in specimens will help researchers refine the methodology proposed here and understand its limitations.

These challenges and research questions highlight the complexity and interdisciplinarity needed in studying environmental health. Our intention here is not to downplay the practical and methodological challenges in addressing these questions, which will demand creative, interdisciplinary teams of ecologists, medical professionals, social scientists, public health experts, communities most impacted by environmental pollution, activists, engineers, historians and others. We believe, however, that these challenges are not insurmountable, and they create space to build diverse teams and partnerships to tackle some of our most significant public health challenges of the twenty-first century.

Conclusions

Natural history collections present a unique opportunity to understand pollution concentrations in the environment over nearly two centuries. These data are especially informative for time periods and locales that lack environmental monitoring data, which is applicable for most pollutants because environmental monitoring often only starts after a pollutant is discovered to be a public health issue. The spatial and temporal scope of specimen collections offer an opportunity to fill these gaps in the environmental record to better understand pollution, its history and origins, and its impacts on the environment and human health.

With a growing recognition of the links between human health, the environments in which we live and work, and the social structures that create and perpetuate environmental inequity, there is an opportunity to expand the One Health framework beyond its emphasis on infectious disease to advance research that tackles the history and impacts of environmental pollution on public health outcomes and environmental inequity. Natural history collections can support this work through their capacity to generate quantitative spatiotemporal data on pollutants. This work will not only require diverse teams and partnerships, but it also calls for increased funding and investment into specimen-based work to further develop collections as essential tools and to build the necessary collaborations across disciplines and communities. With creative and transdisciplinary efforts to leverage collections, we have an unparalleled opportunity to make significant progress in understanding and mitigating the impacts of environmental change.

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BOX 1. A case study to reconstructing lead pollution from natural history specimens: the need for comprehensive data, a proposed methodology, and its implications for public health and policy.

Background	In 2014, the Flint Water Crisis brought lead pollution back to the forefront of national discourse in the U.S.; this public health crisis has real and lasting consequences for those in Flint, and also serves as an important point of public awareness (Olson and Fedinick 2018). However, it is also important to recognize that the discourse around lead exposure in Flint has focused (and continues to focus) on a single pathway of exposure—leaded pipes and drinking water—whereas in the past, public attention focused on other pathways of exposure, like lead-based paint (Mushak and Crocetti 1989, Marino et al. 2011) and leaded gasoline (Annest et al. 1983). Each one of these pathways of lead exposure is of significant public health concern, but treated separately they limit a comprehensive understanding of the full impacts of lead in the environment and on public health.
Problem and its Consequences	We lack comprehensive data on where lead is in the environment. That is, we lack data on the 'life cycle' of lead once it enters the environment: where it goes, how it moves through the environment, the various pathways of human exposure, and how these things have changed across geographic space and through time (i.e., its 'history'), particularly in relation to land-use change, biodiversity loss, and policy (Tovar-Sánchez et al. 2018, Kalani et al. 2021, Levin et al. 2021). As in Flint, lead exposure is often attributed to drinking water, but the movement and cycle of lead through our environments is much more complex and can happen in tandem with other pollutants (e.g., mercury) that are also of significant public health concern. The public health consequences of environmental pollutants like lead are global, and disproportionately impact children, lower income countries, and marginalized communities (IHME 2019, Ritchie and Roser 2022). Without understanding lead pollution levels in the environment—and how these levels have changed through geographic space and time—it remains difficult to: (1) understand the independent and cumulative effects of different pathways of lead exposure, (2) tease apart the independent and cumulative effects of exposure to multiple pollutants, and (3) understand the impacts of chronic low-level lead exposure and its cascading social and health consequences across generations. Understanding these complexities are necessary to inform policy and legal measures to most effectively mitigate harm, protect vulnerable populations, and repair our relationships with the environment and build healthier relationships moving forward.

Solution	Quantifying lead levels in natural history specimens can uniquely help us reconstruct the life cycle of lead in the environment. These datasets would capture the biological component of environmental lead (e.g., identifying organismal burdens of lead, how lead moves through food webs and between aquatic and terrestrial environments). These data could then be paired with complementary datasets that capture abiotic components of lead, like lead in water samples and in sediment cores. By integrating across biotic and abiotic datasets, we could build a comprehensive and foundational understanding of where lead is (and has been) in the environment.
Measuring lead from specimens	Lead concentrations can be quantified from organisms with spectrometry methods. For example, total elemental concentrations of lead can be measured in plant tissues (roots, leaves, bark pockets, growth rings, etc.), lichens, mollusk soft tissues, fungal fruiting bodies, arthropod tissues (the whole organism or products like spider webs), and vertebrate tissues (feathers, hair, scales, bone, kidney, liver, spleen, eggs, etc.). See Supplementary Table 1 for a list of studies that provide detailed methodology for quantifying lead from diverse tissue types using spectrophotometry. While spectrophotometry methods are frequently used to quantify lead burdens in organisms and have been informative for understanding the impacts of lead on the environment, they have two big limitations that hinder their ability for scaling up: (1) the methodology is time consuming and (2) often requires destroying the sample. However, recent methodological advancements with X-ray fluorescence (XRF) allow for non-destructive high-throughput sampling, significantly increasing the rate of data collection without destroying the sample (Specht et al. 2014, Specht et al. 2016). In vertebrates, skeletal lead is the predominant source of body burden (Barry 1975), and Specht and colleagues have been successfully developing XRF methods for quantifying lead concentrations in bones, as well as from blood spots (e.g., Specht et al. 2018, Specht and Weisskopf 2019, Specht et al. 2019, Hampton et al. 2021, Specht et al. 2021). With these types of methodological advances (and future methods development) it will be possible to design feasible sampling schemes to generate a robust understanding of the biological component of environmental lead.
Health implications	Detailed data on the spatial and temporal extent of lead in the environment would provide a quantitative framework for better understanding its consequences on human health and disease pathology, particularly its long-term and transgenerational impacts. For example, these data could be paired with spatially and temporally matched public health datasets, like US Medicare insurance claims for neurological/neurodegenerative conditions, which manifest later in life. Given that Medicare was established in 1965 in the US for individuals over the age of 65, Medicare insurance claim data captures potential health outcomes from over 120 years of environmental exposure. When analyzed in conjunction, these paired datasets could help us better understand correlative links between environmental lead, lifetime exposure risk, and disease pathology. This hypothetical example is one of the many ways in which detailed environmental pollution data could inform our understanding of the health consequences of pollution across time scales (e.g., over someone's lifetime or across generations) that have been previously difficult to address.
Policy implications	How can we understand the impacts of past environmental policy regarding lead without understanding how pollution loads have changed through geographic space and time? Detailed environmental data on lead has both upstream and downstream implications for policy. *Upstream (historical) policy implications*: What role has policy played in producing lead pollution distributions, and what has been the efficacy of past policy reforms designed to mitigate lead pollution? Quantitative temporal lead data would allow us to answer these questions and better understand the impacts and efficacy of policy in meeting its goals. To illustrate this point, in 2017 we reconstructed 135 years of atmospheric black carbon pollution in the U.S. Manufacturing Belt from bird specimens (DuBay and Fuldner 2017). With these data we were able to assess the various roles of federal and city-level

legislation in mitigating black carbon pollution. With future studies, the spatial and temporal specificity of datasets derived from biological collections would allow for policy assessments across various spatial scales of interest (local, regional, federal) as well as various time scales.

Downstream (future) policy implications: Informed by new, quantitative data on environmental lead (and other pollutants), what are effective and equitable policy responses? What information can these data provide for Superfund sites and other federal clean-up efforts or for future land use decisions? Can these data empower vulnerable populations and the communities most impacted by pollutants in their efforts to push for policy measures that best serve their needs and protect their health? How does a better understanding of past policy inform future policy decisions? These are all consequential questions that impact public health and well-being that hinge on a comprehensive understanding of the 'life' and 'history' of pollutants in the environment.

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