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

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Through the industrial era, pollutants have been unevenly distributed in the environment, disproportionately impacting disenfranchised communities. Redressing the unequal distribution of environmental pollution is thus a question of environmental justice and public health that requires policy solutions. However, data on pollutants for many locations and time periods are limited because environmental monitoring is largely reactive—i.e., pollutants are monitored only after they are recognized as harmful and are circulating in the environment at elevated levels. Without comprehensive historical pollution data, it is difficult to understand the full, intergenerational consequences of pollutants on environmental and human health. We assert that biological specimens in natural history collections are an underutilized source of quantitative pollution data for tracking environmental pollutants over two centuries to inform justice-centered policy solutions. Specifically, we: 1) discuss the need for quantitative pollution data in environmental research and its implications for public health and policy, 2) examine the capacity of biological specimens as tools for tracking environmental pollutants through space and time, 3) present a framework for integrating pollution datasets from specimens with spatially and temporally matched human health datasets to inform and evaluate policy, and 4) identify challenges and research directions associated with the use of quantitative pollution datasets. Biological specimens present a unique opportunity to fill critical gaps that address environmental challenges relevant to public health and policy. This work demands interdisciplinary partnerships and inclusive practices to connect data generated from specimens with urgent questions about environmental health and justice.

spatial and temporal sampling | exposure risk | one health | health disparities | environmental justice

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 (1–5). How environmental pollution is (and has been) distributed—and its unequal impacts on different human subpopulations—is thus a question tied to issues of historical inequality, environmental racism, environmental justice, and public health and policy more broadly (3). For example, Colmer et al. (6) show that significant disparities in air pollution exposure have persisted across communities in the continental US over the last four decades, even as overall concentrations of air pollution have dropped across this period. This ability to link pollution exposures to public health and policy decisions requires quantitative data on pollution concentrations in the environment at relevant spatial and temporal scales (3, 7, 8).

Existing studies, even those with decades of pollution data, still lack the temporal and spatial breadth and resolution to capture 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 (9, 10). Thus, to fully understand the links between human health and pollution requires long-term data on when, where, and in what concentration 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 dynamic environments in which we live, which is consequential for developing policies that effectively redress past harm and prevent widening health disparities within communities (11). 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 y, 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 understand the world's biodiversity and evolutionary history (12). Incidentally, these specimens also function as *environmental archives*, preserving

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Fig. 1. An example of how specimens function as environmental archives, preserving pieces of the environments they inhabited. The figure (from ref. 20) compares two Field Sparrows (*Spizella pusilla*) collected within the US 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.

pieces of the environments they inhabited (e.g., Fig. 1) (13, 14). Specimens offer researchers material records of past environments that can be used to quantify spatiotemporal changes in environmental pollution, though this is not without challenges given the nonsystematic sampling of specimens, as well as variation in the data associated with specimens, which can result in spatial and temporal variation in data quality and specimen availability. In a textbook case that led to key environmental legislation in the United States. (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 United States and United Kingdom (15, 16). Bird and fish specimens have also been used to track the rise of metal contamination and microplastics in terrestrial and aquatic environments (e.g., refs. 17–19), and bird specimens have been used to reconstruct over a century of atmospheric pollution across the US Industrial Belt (Fig. 1) (20). 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 (17, 19, 20). Furthermore, the groundwork for using specimens to link pollution to human health has already been done, with decades of research done globally that has demonstrated that concentrations of over a hundred pollutants can be reliably estimated from specimens (Dataset), including some of the most concerning pollutants for human health (e.g., lead, PFAS, particulate pollution, among many others). This capacity of specimens as indicators of environmental health is implicit in GeoHealth and One Health frameworks through their acknowledgement that geography, plant and animal health, and public health are closely intertwined (21, 22).

We assert that natural history collections have unique potential as environmental archives to inform our understanding of 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 the full potential in linking pollution loads and exposure risk to community-level health impacts and policy. Last, 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. We also discuss limitations of the methodology that we propose, potential solutions, and the big questions and challenges to address as a research community moving forward. The work that we propose builds toward an interdisciplinary 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.

The Consequences of Incomplete Data On Historical Pollution

Understanding pollution in the environment is consequential for understanding human health because pollution is one of the most acute forces by which environmental disparities manifest in peoples' lives (23, 24). With growing recognition of the interconnectedness of human, animal, and ecosystem health, it has become increasingly important to understand pollution histories and dynamics across environments to support data-driven efforts to redress past and ongoing harm caused by environmental pollution. The environmental history of DDT highlights this point—with historical data on changing levels of DDT in the environment (e.g., (15, 16), researchers were able to understand its present-day impacts (at the time), which led to key national and international regulations and policy changes, like those outlined in the Stockholm Convention on Persistent Organic Pollutants (25, 26). Quantitative historical pollution data can thus serve present day environmental questions by providing a detailed understanding of how we got here and a basis to estimate past and present impacts.

In 2004, the term "One Health" was first introduced 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" (22). While a One Health framework is a helpful precursor to understand the connections between human health and the environment, we must also consider the sociopolitical and economic systems that shape our environments and maintain pollution in the first place (23, 27). In acknowledging these connections [referred to by sociologists as the political economy of the environment (28)], we have begun to understand human health as also 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 subpopulations. One of the clearest examples of these connections is the impact of US infrastructure and housing policies that have enforced decades of residential placement, zoning, and codified racial segregation practices like redlining across the United States, which is defined as denying financial services to neighborhoods based on racial composition. These practices concentrated marginalized subpopulations in environmentally degraded and polluted areas (24, 29, 30). 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 are politically and economically disenfranchised (24, 31). In the United States, policies and industrial siting decisions disproportionately impact Black, Indigenous and Latinx communities, poorer communities, LGBTQ+ communities, people experiencing greater incidence of mental health illness, and people with disabilities (4, 5, 8, 24, 32). These effects also compound at the intersections of different subpopulations and identities (33). 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 effects (8, 34, 35). Robust data on the environmental conditions that disproportionately affected communities have experienced 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, however, 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 accumulation and life cycle of pollutants in the environment. For example, in 1955 the United States 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 (36). The Air Pollution Control Act established the first national network to monitor air quality, but black carbon pollution in the United States had already peaked decades earlier, and by 1955, levels of black carbon pollution were declining (20, 36). Environmental monitoring as it has been deployed is thus characteristically reactive, resulting in an incomplete record of pollutants in the environment.

Given the reactive nature of environmental monitoring, pollution datasets are often limited to recent decades. For example, in the United States, the EPA began monitoring lead pollution in the 1970s at its advent (37), and the CDC established the Childhood Lead Poisoning Prevention Program in 1995, which put into place nation-wide surveillance of childhood blood lead levels (38). The EPA set a monitoring standard for $PM_{2.5}$ as recent as 1997 (39), and the Dragonfly Mercury Project began in 2009 as a joint effort between the US Geological Survey and National Park Service, and has since become the largest nation-wide assessment of mercury contamination (40). Since the late 1990s, quantitative pollution datasets have been critical for linking pollutants and health impacts, often with remarkable spatial resolution. For example, Henneman et al. uncovered links between mortality risk and $PM_{2.5}$ derived from coal-burning powerplants at the zipcode level in the United States between 1999–2020 (41), and Wu et al. uncovered links between COVID-related deaths and $PM_{2.5}$ exposure at the county level in the United States between 2000–2016 (42). Both studies use $PM_{2.5}$ pollution estimates built by pairing contemporary data sources, like powerplant data, dispersion, and chemical transport models, and satellite measurements of aerosol optical depth (43, 44). However, the data necessary to reconstruct pollution estimates further back in time are sparser, or in most cases, nonexistent.

While current pollution datasets have been invaluable for understanding the origins and impacts of pollution, they are limited in temporal scope, often insufficiently capturing: 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 coproduction and codistribution of multiple pollutants. The extent of data necessary to quantify pollution exposure is necessarily case-specific—data demands will vary depending on the type of pollutant, the question(s) being asked, and the spatial and temporal scale of the problem. However, a general lack of spatially and temporally paired data has constrained our ability to answer longstanding and emerging questions in environmental health, which we address below. While not without limitations, natural history specimens—in their capacity to track environmental change—offer data and historical perspective that can complement current datasets and work in service of epidemiological studies, health equity, and environmental justice.

Natural History Specimens and their use as Bioindicators

Millions of zoological and botanical specimens have been collected throughout much of the world for over two centuries (Figs. 2 and 3) (12). These specimens are housed across hundreds of natural history collections globally and are a source of data. Many of these collections are digitized in web portals like gbif.org and vertnet.org, where specimens and their metadata can be searched. However, for some of the largest collections globally, a small percentage of their holdings have been digitized (45). Additionally, the origins of many collections, like those in the United States and Europe, are inextricably tied to imperialistic and harmful extractive practices of Western science for which acknowledgement only starts a path to restorative justice for the people and places where many of these specimens are from (46–48). We propose that using specimens to understand past environments can help reconnect specimens to the places from which they came to address place-based environmental challenges.

Each specimen has associated metadata that typically includes information about when and where it was collected—dates are often documented to specific calendar day and year, and locations are usually documented at local scales, such as the county level in the United States (as shown in Fig. 4), or township, district, prefecture, etc. in other global locales. However, even if a research question requires specimens with specific locality data, for example specimens with georeferenced latitudes and longitudes, the collections are extensive (Figs. 2 and 3*B*). The collection locality reflects a known area in which the organism interacted with the environment, and the geographic extent of this interaction can be estimated. For example, sedentary organisms like plants and bivalves interact with the environment at hyperlocal scales, while motile organisms, like birds and fish, interact with the environment across broader geographic scales, which can be estimated based on their known ecology and life history.

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 (50). Although sampling biases exist that impact data quality and specimen availability (i.e., sampling effort and data quality vary geographically and temporally), the breadth of sampling spans land-use gradients, land cover types, 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 interest can be seen, for example, in Figs. 2–4.

Since the 1960s, the potential for using plants and animals to understand environmental pollutants has been an active area of scientific research (e.g., refs. 15, 16). For example, studies have examined how animals sequester and bioaccumulate pollutants from the environment in their tissues (feathers, hairs, bones, muscles, organs, exoskeletons, etc.; Dataset). In trees, tar spots and leaf/needle damage reflect exposure to air pollutants like sulfur dioxide and ozone (e.g. ref. 51). Bivalves in aquatic systems, like mussels, filter pollutants from the water column and sequester these

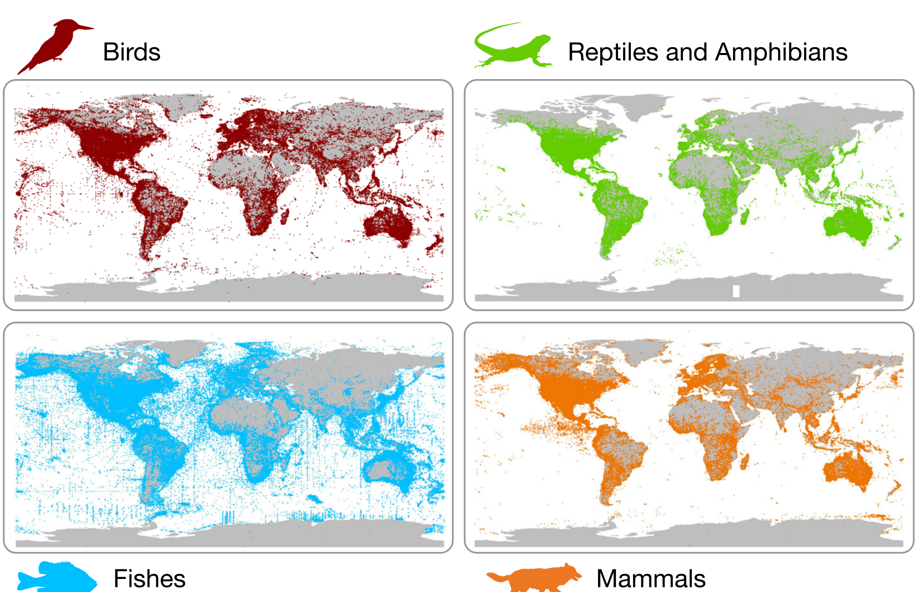

Fig. 2. Global maps showing the extent of vertebrate specimens from over 400 natural history collections. Each point represents an individual georeferenced specimen. Sample sizes: Birds (n = 4,164,205), Squamate Reptiles and Amphibians (n = 4,571,653), Ray-finned Fishes (n = 5,611,362), and Mammals (n = 4,016,041). Maps were compiled from records on GBIF [(49); an aggregate database of global natural history collections] of preserved specimens that included coordinates of where the specimen was collected.

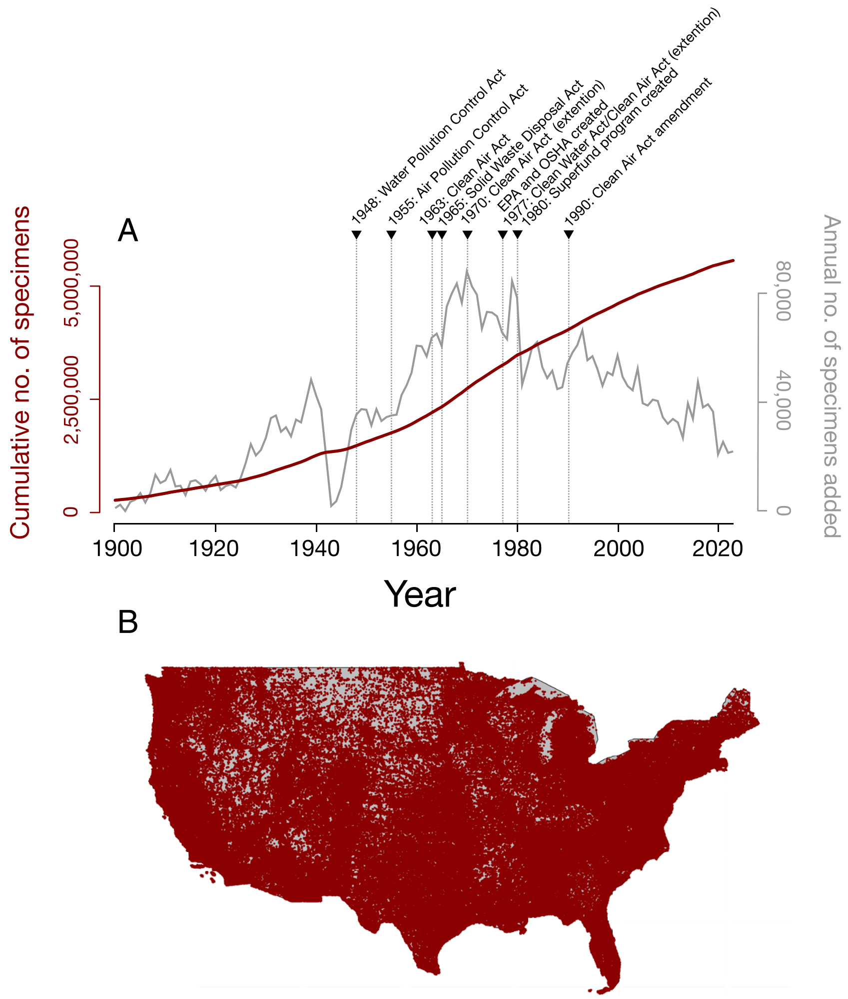

Fig. 3. Vertebrate specimens from the contiguous US from 1900 to 2023, compiled from GBIF (49). (*A*) Specimen acquisition through time with a timeline of key environmental legislation in the United States. The black line shows cumulative specimens in collections through time. The gray line shows the number of specimens entering collections each year. (*B*) Specimen map. Each red point represents a single specimen.

pollutants in soft tissues, which have been measured to assess metal contamination and pollutants from plastics like phthalates and polychlorinated biphenyls (PCBs) (e.g. ref. 52), and fish have been used to assess changes in microplastics in the environment (19). These examples highlight a small subset of studies that have been done globally to document how plants and animals capture pollutants from the environments they inhabit. Various examples throughout the text

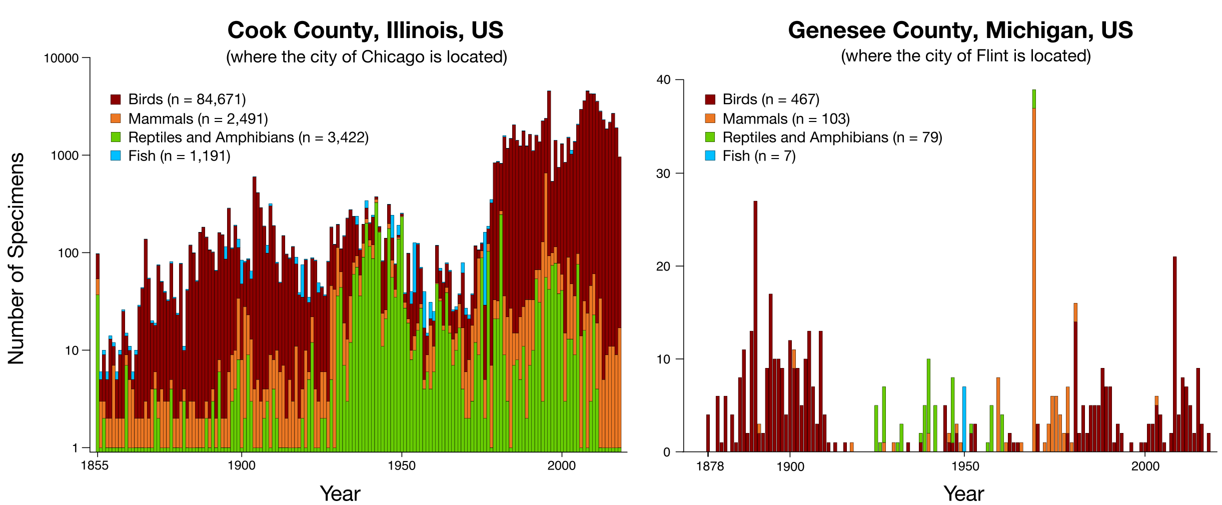

Fig. 4. Examples of vertebrate specimen sample sizes through time from two US counties with long histories of environmental contamination, Cook Co. and Genesee Co., which include the cities of Chicago and Flint, respectively, and their surrounding areas. We present these plots to show the range of variation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

also highlight the diverse pathways in which organisms accumulate pollutants. For example, black carbon particles can accumulate superficially on an organism, such as on bird feathers (Fig. 1), while metals like lead and mercury bioaccumulate in animal tissues, like bone and nails. The pathways through which a pollutant accumulates on or in a specimen can differ based on the physical properties of the pollutants and the biological traits and ecology of the organism, which can inform the resulting temporal and spatial parameters. For example, knowing when a bird species undergoes its annual molt can help establish time intervals for pollutants derived from feather samples. See Dataset for a list of more than one hundred pollutants that have been assessed in most major plant and animal groups.

The motivation for much of the 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, challenges, and steps required to relate specimen-based pollution data to human health outcomes. We address some of these steps and challenges in more detail below.

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 and evolution (50). 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 refs. 53, 54].

Linking Historical Pollution Data with Public Health and Policy

The *environmental archive* feature of natural history specimens makes them uniquely valuable for retroactively 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 and hypothetical case study 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 the transgenerational impacts of pollution exposure, how pollution levels and exposure risk are moderated or exacerbated by policy choices and social contexts, or how exposure risks are 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 and if these links have changed through time. Pollution data from biological specimens could help assess and inform environmental and land-use policy, particularly when paired with pollution data from environmental media like soils, sediments, and ice cores. Pairing biotic (e.g., specimens) and abiotic (e.g., sediments) pollution datasets can help us build a comprehensive understanding of where pollution is in our environments, the relationship between pollution levels in biotic and abiotic systems, and how these dynamics change across space and time.

As this work expands, generalities may emerge with respect to sampling needs when using different types of specimens to address a range of questions that span scales and pollutants. These data could 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 that manifest later in life, like many neurological disorders, and potentially result from long-term exposure to pollutants at low levels (67). Given their high spatial resolution, specimen-based analyses could possibly be used to address these questions at the subpopulation level, as well as understand drivers of individual-level variation within subpopulations. 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 datasets, for example, in linking air quality to health outcomes, like for asthma (68) and COVID-19 mortality (42, 69). What we propose here is to extend these types of methods to robust, quantitative pollution datasets built using time series of natural history specimens.

Big Questions and Challenges Moving Forward

There are several big questions and public health challenges that we can begin to address with robust, spatially dynamic temporal pollution 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

Box 1.

Reconstructing lead (Pb) pollution from natural history specimens: the need for comprehensive data, a proposed methodology, and its implications for public health and policy.

The Problem and its Consequences

In 2014, the Flint Water Crisis brought lead (Pb) pollution back to the forefront of national discourse in the United States; this public health crisis has real and lasting consequences for those in Flint and serves as an important point of public awareness (55). However, it is also important to recognize that the discourse around Pb in Flint focuses on a single pathway of exposure—leaded pipes and drinking water—whereas in the past, public attention focused on other exposure pathways, like lead-based paint (56) and leaded gasoline (57). Each of these pathways is of public health concern, but treated separately they limit a comprehensive understanding of the full impacts of Pb in the environment and on public health. We lack data on the "life cycle" of Pb once it enters the environment: where it goes, how it moves through the environment, the various pathways of exposure, and how these aspects change across space and through time (i.e., its "history"), particularly in relation to land-use change, biodiversity loss, and policy (58, 59).

The public health consequences of environmental pollutants like Pb are global, disproportionately impacting children, lower income countries, and marginalized communities (60, 61). Without understanding how Pb pollution levels have changed through geographic space and time it remains difficult to understand the independent and cumulative effects of different pathways of Pb exposure, and understand the impacts of chronic low-level Pb 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.

Solution

Quantifying Pb levels in natural history specimens can help us reconstruct the life cycle of Pb in the environment. These datasets would capture the biological component of Pb (e.g., identifying organismal burdens of Pb, how Pb moves through food webs and between aquatic and terrestrial environments). These data could then be paired with complementary datasets that capture abiotic components of Pb, like Pb in water samples and sediment cores. By integrating across biotic and abiotic datasets, we could build a comprehensive and foundational understanding of where Pb is (and has been) in the environment.

Measuring Lead from Specimens

Pb concentrations can be quantified from organisms with spectrometry methods. For example, total elemental concentrations of Pb can be measured in plant tissues, lichens, mollusks, fungal fruiting bodies, arthropod tissues, and vertebrate tissues. See Dataset for studies that provide detailed methodology for quantifying Pb from diverse tissue types using spectrophotometry.

Spectrophotometry methods are frequently used to quantify Pb burdens in organisms, but 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 nondestructive high-throughput sampling, significantly increasing the rate of data collection without destroying samples (62, 63). In vertebrates, skeletal Pb is the predominant source of body burden (64), and researchers have been successfully developing XRF methods for quantifying Pb concentrations in bone tissue (e.g., refs. 65, 66). 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 Pb.

Health Implications

Detailed data on the spatial and temporal extent of Pb 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 United States for individuals over the age of 65, Medicare insurance claim data captures potential health outcomes from over 120 y of environmental exposure. When analyzed in conjunction, these paired datasets could help us better understand correlative links between environmental Pb, lifetime exposure risk, and disease pathology. This example is one of the many ways in which detailed environmental pollution data could inform our understanding of the health consequences of pollution across various time scales (e.g., over someone's lifetime or across generations).

Policy Implications

How can we understand the impacts of past environmental policy regarding Pb without understanding how pollution loads have changed through space and time? Detailed environmental data on Pb have upstream and downstream implications for policy.

Upstream (historical) implications: What role has policy played in producing Pb distributions, and what has been the efficacy of past policy to mitigate Pb pollution? Quantitative Pb data would allow us to answer these questions and better understand the efficacy of policy in meeting its goals. 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) implications: Informed by new, quantitative data on environmental Pb, 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 communities most impacted by pollutants in their efforts to push for policy measures that 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 that hinge on a comprehensive understanding of the "life" and "history" of pollutants in the environment.

sciences. Below we highlight longstanding and emerging questions that robust pollution datasets will help clarify and contribute to:

(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 (70–74): 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 (75–78): Pollutants often covary through space and time, 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 spatial and temporal 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 (31). The spatial and temporal breadth of natural history specimens makes them well suited to help tackle these challenges by capturing the subtleties of how pollutants covary across the environment.
(3) Calibrating historical levels of exposure and deposition with modern sample data: We can assess trends of pollution through time, but how do pollutant concentrations in an individual specimen relate to the concentrations being emitted and deposited in the environment? By pairing modern environmental monitoring data with pollutant concentrations in specimens sampled at present day, we can calibrate pollution models to better estimate historical pollution concentrations in the environment. There is a lot that we can learn by understanding relative trends in historical pollution but having estimates of environmental concentrations can help us tackle some of the other challenges mentioned here.
(4) Understanding how pollutants move through the environment and biological systems (74, 79–83): 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 and understanding when and how human exposure is coupled or decoupled from nonhuman 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 do animal movements influence local concentrations and distributions of pollutants (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, climate change, 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.
(7) Continued and expanded investment in natural history collections: While natural history collections are expansive, there is an apparent decline in the rate of acquisition in recent decades (Fig. 3). Broadening the use of collections to support the needs of pollution-based human health and environmental justice research should be accompanied by increasing support of these institutions and efforts to coordinate research networks and build cross-disciplinary partnerships.

These research questions and challenges 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.

Limitations of the Proposed Method

While natural history collections can be used to generate vast amounts of data on environmental pollutants, they are not without their limitations. First, there is uneven sampling across space and time (Figs. 2–4). In general, specimens are more spatially sparse the further back in time, which may limit the spatial resolution for some questions and time periods. However, these sampling biases are not uniform; in many places contemporary restrictions on collecting specimens have resulted in declining specimen coverage in more recent decades. This means that for some fine scale questions, there may be data constraints; to better understand this limitation, work is needed to assess how much sampling is necessary to accurately reconstruct the levels of different pollutants circulating in the environment. By developing a better understanding of the uncertainty with respect to smaller sample sizes, it will be possible to constrain specimen-based pollutant datasets to the temporal and geographic scales at which they are likely to be accurate, which may be pollutant specific and vary through space and time. While uneven sampling may limit some analyses, for many areas—particularly those with high population densities where these questions are particularly urgent—there tend to be rich historical collections (Figs. 3*B* and 4). Furthermore, while specimens have sampling limitations, in many places around the world direct monitoring of environmental pollutants is scarce or nonexistent, and in these contexts, specimens may be particularly useful, even given their sampling limitations.

Second, while extensive work has been done to test whether specimens are accurate bioindicators of environmental pollution for a wide range of pollutants, less is known about how these environmental levels translate to human exposure. However, this type of work is starting to be done, with promising results. For example, lead levels in house sparrows can accurately predict blood lead levels in children at small spatial scales (the neighborhood level) and through time (84). While many organisms share pollution exposure pathways with humans, there will be some variation among settings, pollutants, and taxa. Understanding the links between environmental pollution levels as quantified in specimens and human exposure will thus require collaborative work between interdisciplinary teams of experts in organismal biology, ecotoxicology, and human health. Establishing general guiding principles (e.g., human commensal species are best for indicating urban exposure to pollutants) is a critical first step in unlocking the potential of specimen-based approaches to reconstructing historical pollution datasets.

Third, museum specimens are finite resources, and many methods for measuring pollutants from biological specimens are destructive (e.g., combusting tissues to understand their composition). Destructive sampling requires that researchers work closely with museum curators within existing frameworks for the responsible use of specimens. Most collections have protocols in place to assess destructive sampling requests. New technologies, however, are emerging that will enable pollutant information to be obtained from specimens through nondestructive sampling techniques; these methods should be invested in and used whenever possible. While there are extensive historical collections held in museums, collecting has been more limited since the first half of the 20th century (Fig. 3*A*). The type of work that we propose here is another example of the many uses of specimens that would have been inconceivable by the earliest collectors, and what we propose would not be possible with other types of information often suggested as alternatives to specimen collecting. Researchers who are interested in using specimens to reconstruct pollution landscapes should invest in relationships with museum scientists; such relationships could support ongoing museum efforts and inform museum practices, as certain specimen preparation methods may prove particularly useful for this type of work.

Conclusions

Natural history collections present a unique opportunity to understand pollution concentrations in the environment over 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. Future potential for specimens to reconstruct pollution levels moving forward will rely on continued specimen collection and expanded investment in natural history museum infrastructure.

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, digitization, 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 interdisciplinary efforts to leverage collections, we have an unparalleled opportunity to make significant progress in understanding and mitigating the impacts of environmental change.

Data, Materials, and Software Availability. There are no data underlying this work.

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1. United Church of Christ Commission for Racial Justice, *Toxic Wastes and Race in the United States: A National Report on the Racial and Socio-Economic Characteristics of Communities with Hazardous Waste Sites* (Public Data Access, 1987).
2. R. D. Bullard, *Dumping in Dixie: Race, Class, and Environmental quality* (Routledge, 2018).
3. P. Mohai, D. Pellow, J. T. Roberts, Environmental justice. *Annu. Rev. Environ. Resour.* **34**, 405–430 (2009).
4. L. Goldsmith, M. L. Bell, Queering environmental justice: Unequal environmental health burden on the LGBTQ+ community *Am. J. Public Health* **112**, 79–87 (2022).
5. C. W. Tessum *et al.*, 5 polluters disproportionately and systemically affect people of color in the United States. *Sci. Adv.* **7**, eabf4491 (2021).

6. J. Colmer, I. Hardman, J. Shimshack, J. Voorheis, Disparities in PM2. 5 air pollution in the United States. *Science* **369**, 575–578 (2020).
7. Institute of Medicine (US) Committee on Environmental Justice, *Toward Environmental Justice: Research, Education, and Health Policy Needs* (National Academies Press, 1999).
8. D. Payne-Sturges, G. C. Gee, National environmental health measures for minority and low-income populations: Tracking social disparities in environmental health. *Environ. Res.* **102**, 154–171 (2006).
9. P. J. Landrigan *et al.*, Early environmental origins of neurodegenerative disease in later life. *Environ. Health Perspect.* **113**, 1230–1233 (2005).
10. D. Kim, Z. Chen, L.-F. Zhou, S.-X. Huang, Air pollutants and early origins of respiratory diseases. *Chronic Diseases Transl. Med.* **4**, 75–94 (2018).
11. M. C. Arcaya, J. F. Figueroa, Emerging trends could exacerbate health inequities in the United States. *Health Aff.* **36**, 992–998 (2017).
12. National Academies of Sciences, Engineering, and Medicine, *Biological Collections: Ensuring Critical Research and Education for the 21st Century* (National Academies Press, 2020).
13. K. Winker, Natural history museums in a post-biodiversity era. *BioScience* **54**, 455–459 (2004).
14. C. J. Schmitt, J. A. Cook, K. R. Zamudio, S. V. Edwards, Museum specimens of terrestrial vertebrates are sensitive indicators of environmental change in the Anthropocene. *Philos. Trans. R Soc. Lond. B Biol. Sci.* **374**, 20170387 (2019).
15. D. Ratcliffe, Decrease in eggshell weight in certain birds of prey. *Nature* **215**, 208–210 (1967).
16. J. J. Hickey, D. W. Anderson, Chlorinated hydrocarbons and eggshell changes in raptorial and fish-eating birds. *Science* **162**, 271–273 (1968).
17. A. E. Vo, M. S. Bank, J. P. Shine, S. V. Edwards, Temporal increase in organic mercury in an endangered pelagic seabird assessed by century-old museum specimens. *Proc. Natl. Acad. Sci. USA* **108**, 7466–7471 (2011).
18. A. L. Bond, K. A. Hobson, B. A. Branfireun, Rapidly increasing methyl mercury in endangered ivory gull (Pagophila eburnea) feathers over a 130 year record. *Proc. Biol. Sci.* **282**, 20150032 (2015).
19. L. Hou *et al.*, A fish tale: A century of museum specimens reveal increasing microplastic concentrations in freshwater fish. *Ecol. Appl.* **31**, e02320 (2021).
20. S. G. DuBay, C. C. Fuldner, Bird specimens track 135 years of atmospheric black carbon and environmental policy. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 11321–11326 (2017).
21. American Geophysical Union, Geohealth Fact Sheet. https://www.agu.org/-/media/files/share-and-advocate-for-science/fact-sheets/016_3897_geohealth-fact-sheet.pdf [Accessed 20 April 2025].
22. Centers for Disease Control and Prevention, About one health. https://www.cdc.gov/one-health/about/index.html [Accessed 20 April 2025].
23. M. Murphy, Chemical regimes of living. *Environ. Hist.* **13**, 695–703 (2008).
24. D. Taylor, *Toxic Communities* (New York University Press, 2014).
25. J. W. Grier, Ban of DDT and subsequent recovery of reproduction in bald eagles. *Science* **218**, 1232–1235 (1982).
26. P. L. Lallas, The Stockholm convention on persistent organic pollutants. *Am. J. Int. L.* **95**, 692–708 (2001).
27. M. Liboiron, *Pollution is Colonialism* (Duke University Press, 2021).
28. T. K. Rudel, J. T. Roberts, J. Carmin, Political economy of the environment. *Annu. Rev. Sociol.* **37**, 221–238 (2011).
29. M. Singer, Down cancer alley: The lived experience of health and environmental suffering in Louisiana's chemical corridor. *Med. Anthropol. Q.* **25**, 141–163 (2011).
30. H. M. Lane, R. Morello-Frosch, J. D. Marshall, J. S. Apte, Historical redlining is associated with present-day air pollution disparities in US cities. *Environ. Sci. Technol. Lett.* **9**, 345–350 (2022).
31. T. F. Begum, D. O. Carpenter, Review of environmental contamination at Akwesasne and associated health outcomes. *J. Indig. Res.* **10**, 1 (2022).
32. J. Chakraborty, Disparities in exposure to fine particulate air pollution for people with disabilities in the US. *Sci. Total Environ.* **842**, 156791 (2022).
33. P. Homan, T. H. Brown, B. King, Structural intersectionality as a new direction for health disparities research. *J. Health Soc. Behav.* **62**, 350–370 (2021).
34. J. F. Culhane, R. L. Goldenberg, Racial disparities in preterm birth. *Semin. Perinatol.* **35**, 234–239 (2011).
35. T. W. Collins, S. E. Grineski, D. X. Morales, Sexual orientation, gender, and environmental injustice: Unequal carcinogenic air pollution risks in greater Houston. *Ann. Am. Assoc. Geogr.* **107**, 72–92 (2017).
36. D. Stradling, *Smokestacks and Progressives* (Johns Hopkins University Press, 1999).
37. T. Dignam, R. B. Kaufmann, L. LeStourgeon, M. J. Brown, Control of lead sources in the United States, 1970–2017: Public health progress and current challenges to eliminating lead exposure. *J. Public Health Manag. Pract.* **25**, S13–S22 (2019).
38. A. S. Ettinger, M. L. Leonard, J. Mason, CDC's lead poisoning prevention program: A long-standing responsibility and commitment to protect children from lead exposure. *J. Public Health Manag. Pract.* **25**, S5–S12 (2019).
39. Environmental Protection Agency, Air Quality Designations for Particle Pollution. https://www.epa.gov/particle-pollution-designations [Accessed 20 April 2025].
40. U.S. Geological Survey, Dragonfly mercury project. https://geonarrative.usgs.gov/dmp/ [Accessed 20 April 2025]
41. L. Henneman *et al.*, Mortality risk from United States coal electricity generation. *Science* **382**, 941–946 (2023).
42. X. Wu, R. C. Nethery, M. B. Sabath, D. Braun, F. Dominici, Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis. *Sci. Adv.* **6**, eabd4049 (2020).
43. L. R. Henneman, C. Choirat, C. Ivey, K. Cummiskey, C. M. Zigler, Characterizing population exposure to coal emissions sources in the United States using the HyADS model. *Atmos. Environ.* **203**, 271–280 (2019).
44. A. Van Donkelaar, R. V. Martin, C. Li, R. T. Burnett, Regional estimates of chemical composition of fine particulate matter using a combined geoscience-statistical method with information from satellites, models, and monitors. *Environ. Sci. Technol.* **53**, 2595–2611 (2019).
45. K. Norris *et al.*, Unlocking avian museum collections to enable and advance environmental change research. *Ibis* **166**, 315–322 (2024).
46. J. M. MacKenzie, *Imperialism and the Natural World* (Manchester University Press Manchester, 1990).
47. C. Quintero Toro, *Birds of Empire, Birds of Nation: A History of Science, Economy, and Conservation in United States-Colombia Relations* (Ediciones Uniandes-Universidad de los Andes, 2012).
48. S. DuBay, D. H. Palmer Droguett, N. Piland, Global inequity in scientific names and who they honor. (2020), https://www.biorxiv.org/content/10.1101/2020.08.09.243238v5.full.pdf.
49. Global biodiversity information facilty. https://www.gbif.org/ [Accessed 20 April 2025]
50. M. S. Webster, *The Extended Specimen: Emerging Frontiers in Collections-Based Ornithological Research* (CRC Press, 2017).
51. R. Bevan, G. Greenhalgh, Rhytisma acerinum as a biological indicator of pollution. *Environ. Pollut.* **1970**, 271–285 (1976).
52. I. Marigómez *et al.*, Combined use of native and caged mussels to assess biological effects of pollution through the integrative biomarker approach. *Aquat. Toxicol.* **136**, 32–48 (2013).
53. J. A. Cook *et al.*, Integrating biodiversity infrastructure into pathogen discovery and mitigation of emerging infectious diseases. *BioScience* **70**, 531–534 (2020).
54. J. P. Colella *et al.*, Leveraging natural history biorepositories as a global, decentralized, pathogen surveillance network. *PLoS Pathog.* **17**, e1009583 (2021).
55. E. Olson, K. P. Fedinick, What's in your water? Flint and beyond. https://www.nrdc.org/sites/default/files/whats-in-your-water-flint-beyond-report.pdf [Accessed 20 April 2025].
56. P. Mushak, A. F. Crocetti, Determination of numbers of lead-exposed American children as a function of lead source: Integrated summary of a report to the US Congress on childhood lead poisoning. *Environ. Res.* **50**, 210–229 (1989).
57. J. L. Annest *et al.*, Chronological trend in blood lead levels between 1976 and 1980. *N. Engl. J. Med.* **308**, 1373–1377 (1983).
58. T. J. Kalani *et al.*, One map: Using geospatial analysis to understand lead exposure across humans, animals, and the environment in an urban US city. *One Health* **13**, 100341 (2021).
59. R. Levin *et al.*, The urban lead (Pb) burden in humans, animals and the natural environment. *Environ. Res.* **193**, 110377 (2021).
60. Institute for Health Metrics and Evaluation, GBD compare. https://www.healthdata.org/data-tools-practices/interactive-visuals/gbd-compare [Accessed 20 April 2025]
61. H. Ritchie, M. Roser, Lead pollution, our world in data. https://ourworldindata.org/lead-pollution [Accessed 20 April 2025].
62. A. J. Specht, M. Weisskopf, L. H. Nie, Portable XRF technology to quantify Pb in bone in vivo. *J. Biomark.* **2014**, 398032 (2014).
63. A. J. Specht *et al.*, XRF-measured bone lead (Pb) as a biomarker for Pb exposure and toxicity among children diagnosed with Pb poisoning. *Biomarkers* **21**, 347–352 (2016).
64. P. Barry, A comparison of concentrations of lead in human tissues. *Occup. Environ. Med.* **32**, 119–139 (1975).
65. A. J. Specht, K. E. Kirchner, M. G. Weisskopf, M. A. Pokras, Lead exposure biomarkers in the common loon. *Sci. Total Environ.* **647**, 639–644 (2019).
66. J. O. Hampton, A. J. Specht, J. M. Pay, M. A. Pokras, A. J. Bengsen, Portable X-ray fluorescence for bone lead measurements of Australian eagles. *Sci. Total Environ.* **789**, 147998 (2021).
67. B. Ritz, Y. Yu, Invited perspective: Air pollution and dementia: Challenges and opportunities. *Environ. Health Perspect.* **129**, 081301 (2021).
68. M. S. Friedman, K. E. Powell, L. Hutwagner, L. M. Graham, W. G. Teague, Impact of changes in transportation and commuting behaviors during the 1996 Summer Olympic Games in Atlanta on air quality and childhood asthma. *JAMA* **285**, 897–905 (2001).
69. G. H. Kerr, D. L. Goldberg, S. C. Anenberg, COVID-19 pandemic reveals persistent disparities in nitrogen dioxide pollution. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022409118 (2021).
70. M. D. Anway, A. S. Cupp, M. Uzumcu, M. K. Skinner, Epigenetic transgenerational actions of endocrine disruptors and male fertility. *Science* **308**, 1466–1469 (2005).
71. C. W. Schmidt, Uncertain inheritance: Transgenerational effects of environmental exposures. *Environ. Health Perspect.* **121**, A298–A303 (2013).
72. M. K. Hoke, T. McDade, Biosocial inheritance: A framework for the study of the intergenerational transmission of health disparities. *Ann. Anthropol. Pract.* **38**, 187–213 (2014).
73. Q. Di *et al.*, Air pollution and mortality in the Medicare population. *N. Engl. J. Med.* **376**, 2513–2522 (2017).
74. E. Nilsen *et al.*, Critical review: Grand challenges in assessing the adverse effects of contaminants of emerging concern on aquatic food webs. *Environ. Toxicol. Chem.* **38**, 46–60 (2019).
75. Environmental Protection Agency, The multi-pollutant report: technical concepts and examples. https://archive.epa.gov/airquality/aqmp/web/pdf/20080702_multipoll.pdf [Accessed 20 April 2025].
76. F. Dominici, R. D. Peng, C. D. Barr, M. L. Bell, Protecting human health from air pollution: Shifting from a single-pollutant to a multipollutant approach. *Epidemiology* **21**, 187–194 (2010).
77. C. Billionnet, D. Sherrill, I. Annesi-Maesano, Estimating the health effects of exposure to multi-pollutant mixture. *Ann. Epidemiol.* **22**, 126–141 (2012).
78. I. Levy, C. Mihele, G. Lu, J. Narayan, J. R. Brook, Evaluating multipollutant exposure and urban air quality: Pollutant interrelationships, neighborhood variability, and nitrogen dioxide as a proxy pollutant. *Environ. Health Perspect.* **122**, 65–72 (2014).
79. L. A. Wallace, Comparison of risks from outdoor and indoor exposure to toxic chemicals. *Environ. Health Perspect.* **95**, 7–13 (1991).
80. Z. Tang, B. Engel, B. C. Pijanowski, K. Lim, Forecasting land use change and its environmental impact at a watershed scale. *J. Environ. Manage.* **76**, 35–45 (2005).
81. K. E. Schilling, M. K. Jha, Y. K. Zhang, P. W. Gassman, C. F. Wolter, Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. *Water Resour. Res.* **44**, 12 (2008).
82. R. F. Lepak *et al.*, Mercury source changes and food web shifts alter contamination signatures of predatory fish from Lake Michigan. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 23600–23608 (2019).
83. L. Li *et al.*, Development and evaluation of a holistic and mechanistic modeling framework for chemical emissions, fate, exposure, and risk. *Environ. Health Perspect.* **129**, 127006 (2021).
84. M. M. Gillings *et al.*, House sparrows as sentinels of childhood lead exposure. *Environ. Sci. Technol.* **58**, 0028–10040 (2024).