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The Socio-Exposome: Advancing Exposure Science and Environmental Justice in a Post-Genomic Era

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Abstract

We propose the *socio-exposome* as a conceptual framework for integrative environmental health research. Environmental scientists coined the term "*exposome"* with the goal of inventorying and quantifying environmental exposures as precisely as scientists measure genes and gene expression. To date, the exposome's proponents have not thoroughly engaged social scientific theoretical and methodological expertise, although the exclusion of sociological expertise risks molecularizing complex social phenomena and limiting the possibility of collective action to improve environmental conditions. As a corrective, and to demonstrate how "omic" technologies could be made more relevant to public health, our *socio-exposome* framework blends insights from sociological and public health research with insights from environmental justice scholarship and activism. We argue that environmental health science requires more comprehensive data on more and different kinds of environmental exposures, but also must consider the socio-political conditions and inequalities that allow hazards to continue unchecked. We propose a multidimensional framework oriented around three axes: individual, local, and global, and suggest some sociomarkers and data sources that could identify exposures at each level. This framework could also guide policy, by creating a predictive framework that helps communities understand the repercussions of corporate and regulatory practices for public health and social justice.

1. Introduction

In this paper, we propose a conceptual framework to guide research on assessing the health effects of environmental exposures, the *socio-exposome*. This concept responds to, yet extends, recent efforts by environmental scientists and molecular epidemiologists to characterize and measure environmental exposures from the periconceptual period throughout the life course (Lu et al. (2003); Lu et al. (2010)). Advocates for this approach have coined the term 'the exposome,' to refer to a person's life-time complement of

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exposures. Simply stated, the goal of exposome research is to measure environmental exposures as precisely as scientists can now measure genes and gene expression (Wild (2005); (2012)). The exposome paradigm illustrates how contemporary environmental health science has begun to take seriously the challenge of measuring exposure as it actually occurs – in complex, layered, in-situ contexts, rather than under laboratory conditions. Moreover, the original framers of the exposome concept suggested that it should assess a broad array of factors, ranging from individual behaviours such as diet and exercise to social determinants of health such as social capital, urban-rural environments, and climate. However, there has been little agreement on how these exposures could be operationalized or how they could be measured. Perhaps not surprisingly, initial applications of the exposome have been less apt to measure social determinants of health and have instead focused primarily on individual-level exposures (Rappaport et al. 2010). In this regard, the exposome has come to resemble other contemporary life science projects, such as epigenetics (Landecker (2011); Darling et al. (2016); Niewöhner (2011); Darling et al. (2016)), which have also embraced a central concern of the social sciences, i.e., how to measure the environment and its effects, but which too often fail to engage social scientific expertise in how to study the social world, or, indeed, to even recognize the rich empirical work already being done in this vein in the social sciences. We argue, however, that without a thorough engagement with the theoretical and methodological expertise of the social sciences, there is a very real risk that exposome research could molecularize complex social phenomena, reducing the social experiences that condition population-level variations in exposures to individual-level molecular-level differences (Shostak et al. 2015). However unintentionally, this reductionism can limit the possibility of collective social action to improve environmental conditions, by excluding the social determinants of exposure from scientific discourse.

We find parallels between exposome research and other recent, high-throughput technologies that have promised to revolutionize biomedical science, most notably the high expectations and eventual disappointment that surrounded the completion of the Human Genome Project (HGP). Exposome research could proceed along one of two paths—it could either follow the path of the genome and take a radically individualized turn (toward so-called personalized medicine initiatives), or, more optimistically, it could produce a more holistic and multilayered assessment of social, political, economic environments and how they interact to influence health. We believe that environmental health scientists should remain committed to the broad scope of the original exposome concept, and continue to refine tools and methods to capture the broadest possible array of environmental exposures and analyse them as multileveled phenomena, and we believe that environmental sociologists could be helpful and productive partners in this intellectual project. Inquiry in this vein could make exposome science more relevant to public health than the first wave of genomic science has proven to be.

We offer a multilevel framework to organize our thinking about what constitutes exposures, and to structure data collection and analytic techniques that will allow scientists to draw connections across levels, thus connecting biological disease pathways to the social and environmental forces that give rise to them. Our socio-exposome offers a scaffolding to integrate environmental exposure data from three levels of analysis: individual, local, and global. At the most basic level, it is critically important to capture data at the level of the individual subject—although we recognize the dangers and limitations of molecularizing social phenomena, we acknowledge the importance of knowing what people have been exposed to, as well as when, how, and how much. The next level of our framework is the local, or community level. We argue that exposome research must capture social forces that bear on community health (e.g., government and corporate practices, area-wide measures of pollution or violent crime, features of the built environment such as transit systems or food deserts). The third level in our framework assesses national or global forces. This level would assess how broad changes in social organization (e.g., urbanization, immigration, deindustrialization) affect patterns of settlement, migration, and citizenship and the consequences those patterns have for the distribution of and exposure to hazards. In this paper, we offer some examples of sociomarkers that could be used to measure exposures at each level, and suggest some specific data sources that either already exist or could be collected to measure them.

Environmental sociologists have much to offer in cross-disciplinary collaborative research on environmental exposures. We recognize that some social scientists have been reluctant to incorporate genetic or biological constructs in their research for fear of biological determinism, but we believe that it is vitally important to engage in dialogue with exposure scientists to critique formulations of the exposome before this branch of science (which has already begun to attract research investments to launch high-visibility projects) matures in ways that negate the irreducibly social aspects of exposures and their consequences. Secondarily, we also address our article to exposure scientists themselves, and throughout the paper we illustrate how social and political processes operate at various levels of analysis (from molecular to global). Finally, we hope that policymakers and funders will embrace the socio-exposome framework and renew their commitment to funding transdisciplinary teams, in both academic and applied settings, who can explore a holistic model of environmental health. Understanding the exposome is a prototypical transdisciplinary problem, one that provocatively illustrates both the rewards and risks inherent in contemporary bioscience (Brown 2015). Ensuring that a wide range of voices and disciplinary expertise participate in characterizing the exposome is the best way to ensure that it fulfils its potential as a tool that can transform our understanding of health and disease, rather than a scientific trend that sociologists react to and critique.

2. A Cautionary Tale: Researching Environmental Exposures in the 'Omics' Era

We find parallels and cautionary tales for the exposome by examining the recent history of what has unfolded in genomic medicine. Scientists and social scientists alike have characterized the post-genomic era as a time of both euphoria and disappointment. Policymakers and scientists heralded the completion of the HGP in 2003 with bold pronouncements that the public could soon expect dramatic benefits in health, both in our ability to personalize medical care based on an individual's genomic profile, and that the widespread application of personalized medicine would lead to improved population health (Collins 2004). As these improvements failed to materialize, however, even ardent champions of genomics modulated their expectations, describing the genome map as foundational research that was necessary to identify biological pathways to disease, and acknowledging the need to study gene-environment interactions (Guttmacher et al. (2005); Olden et al. (2011); Green et al. (2011)).

Despite this gesture towards the importance of gene-environment interactions, the years immediately following completion of the HGP were dominated by efforts to mine the genome for direct effects of genetic variants on common diseases. The method most commonly employed in this era was the genome-wide association study (GWAS). The GWAS method essentially amounted to a fishing expedition; a non-hypothesis driven approach with a very high threshold of statistical significance to protect against spurious associations (Feero et al. 2010). Its proponents claimed that this “unbiased” approach would quickly identify associations between genetic variants and human health outcomes and that these variants could become the focus for the development of targeted therapies. Between 2005 and 2013, more than 1600 GWAS studies were published, identifying putative associations between ~2000 genetic variants and more than 300 possible diseases, including serious public health burdens such as asthma, heart disease, diabetes, and cancer, and less serious conditions such as restless leg syndrome (Manolio 2013). These GWAS studies appeared in top-ranking biomedical journals and were often reported in the popular press as potential breakthroughs. Champions of genomics (and this analytic method) were often disappointed, however, in discovering that most of these associations were small, and accounted for only a modest proportion of disease risk.

This “unbiased” approach to mining the genome for predictors of common disease was entirely consonant with the individualized paradigm of disease causation that dominated epidemiologic research throughout the 20th century. This so-called “dominant epidemiological paradigm (DEP)” largely ascribes illness to individuals’ innate susceptibilities or their lifestyle choices, rather than to broader social or environmental conditions. It is also consistent with a downstream model of medical care that proposes to cure rather than prevent disease (Brown 2007). In this framework, sickness is often seen as a moral failure, rather than a result of environmental conditions, policy decisions, or structural inequities. This type of inquiry biases and narrows the causal narratives about the origins of disease, by diverting our attention toward individual-level genetic factors or lifestyle choices and away from the social and political processes that condition the production of social goods or that drive the manufacture and distribution of hazardous substances. Epidemiologic research under the DEP has been criticized (by scientists working within this field and by social scientists) as atheoretical, and incapable of explaining causal pathways that link exposures to disease (Wing (2000); Shim et al. (2010); Susser et al. (1996a); Susser et al. (1996b); Pearce (1996)). In the waning decades of the 20th century, the discipline of epidemiology endured a protracted war between those who ascribed to the DEP, and a small but vocal minority who favoured a more deductive, theory-driven approach that would better account for historical patterns of population health and the structural inequities that produce health inequalities (Shim et al. 2010).

Exposome proponents face a conundrum similar to the one faced by geneticists and epidemiologists when the HGP was completed in 2003. They could embark immediately on efforts to inventory environmental exposures and rapidly exploit them in the kind of atheoretical, “unbiased” studies (such as the GWAS approach) that dominated the first decade of the post-genomic era. Or they could follow a path of theoretically-driven science that seeks to link environmental exposures and genetic variants to disease outcomes along precise and multilayered pathways that account not only for biological processes of disease formation, but also consider the social, political, and economic forces that create vulnerabilities to exposure. Viewed in this way, scientists proposing the exposome face two kinds of challenges: a pragmatic one (i.e., how to obtain and organize data on multi-layered environmental exposures) and an epistemological one (i.e., what paradigm of disease causation should we embrace, or how should we theorize gene-environment interactions).

To be fair, the pragmatic challenges in assessing environmental exposures are far from trivial. Despite scientific consensus that measuring environmental exposures is critical to understanding human health and illness, and despite estimates suggesting that up to 70–90% of disease risk can be accounted for by environmental rather than genetic factors (Rappaport et al. 2010), our ability to measure environmental exposures and their effects lags far behind our capacity to measure genes and their effects. A landmark report by the Trust for America’s Health in 2001 lamented the fact that although U.S. regulatory agencies conduct routine surveillance of air and water quality, there is no infrastructure in place for systematically assessing human exposure to contaminants of concern, such as persistent organic pollutants, pesticides, and heavy metals. Indeed, the completion of the HGP was followed almost immediately by calls for larger and more ambitious prospective cohort studies and for the creation of biobank projects that would make it easier to explore questions about gene-environment interactions (Collins (2004); Foster et al. (2005); Manolio et al. (2012)). Biobank studies have been launched in the UK, Canada, and Japan (Barbour (2003); Peakman et al. (2008)), but to date they have devoted far less effort to capturing data about real-world environmental exposures than they have in exploiting readily-available data from electronic medical records. Indeed, a common critique of science in the post-genomic era is that is that these endeavours could more properly be said to investigate the *effect* of toxic exposures, while lacking an approach for characterizing the social environment *per se* (Landecker (2011); Niewöhner (2011)).[1]

Conversely, the exposome may follow an alternative pathway, one that is already being developed by scholars in environmental health science and which seeks to understand environmental exposures as complex, socially mediated phenomena. Here we highlight just three ways this type of exposure science diverges from the atheoretical enterprise pursued in the DEP and in first-generation GWAS studies. First, toxicologists have shifted from Paracelsus’ proclamation that the ‘dose makes the poison,’ to understanding that the ‘timing makes the poison,’ based on endocrine disruption research that has shown that low doses can

[1]Despite the sobering realization that GWAS studies would not quickly yield compelling evidence of direct associations between genetic variants and common chronic diseases, many scientists have embraced the basic analytic method, including some who are interested in studying environmental exposures or gene-environment interactions. To make matters even more confusing, the acronym EWAS has been adopted both by scientists who do epigenome-wide association studies (i.e., searching for correlations between common diseases and genetic alterations that affect gene function without altering DNA sequence) (Gemma and Rakyan 2010) and by those who do environment-wide association studies (i.e., searching for correlations between common diseases and biological markers that document exposure to common chemicals and pesticides) (Patel et.al. 2010). Although these EWAS studies purport to study gene-environment interactions or environmental predictors of disease, respectively, they mimic the analytic shortcomings of the GWAS era that we identified earlier, i.e., an “unbiased” attempt to identify predictors without a theoretically informed basis for linking exposures and outcomes, and measuring the effects of environmental exposures rather than the social conditions that give rise to those exposures.

sometimes produce toxic effects not seen at high doses (Colborn et al. 1996). Second, and relatedly, is the rise of the 'windows of development' approach, whereby exposures at different stages of pre-conceptual, fetal, and post-fetal development may have vastly different consequences on health outcomes. For example, women who are exposed to cigarette smoke, ionizing radiation, or DDT during puberty have a greatly increased risk of breast cancer compared to women who were exposed to these toxicants later in life (Lash et al. (1999); Tokunaga et al. (1987); Clemons et al. (2000); Cohn et al. (2007)). Third, academic researchers, environmental advocacy groups, and public health agencies have pursued biomonitoring projects to more accurately characterize body burden, or the accumulation of environmental toxicants in people by sampling blood, urine, breast milk, and cord blood (Environmental Working Group (2003); Brody et al. (2009); Zota et al. (2008); Crinnion (2010)). Fourth, exposure science models are advancing to account for chemical interaction, persistence, and endocrine disruption, and have begun to measure cumulative exposures (NRC 2012). Each of these innovations represents an attempt to measure environmental exposures in the broadest possible sense; the exposome could fit well in this arena of research.

In short, the notion of the exposome has emerged as a potentially important and timely alternative to the limitations of conventional "omic" approaches. But if efforts to characterize and measure the exposome ignore decades of sociologically-informed research documenting the social structures and power inequities that shape the unfair distribution of exposures, the exposome might just serve to further shore up the individualized model of illness causation, rather than illuminating the complex and multifactorial nature of human health and illness (Shostak and Moinester 2015b).

3. Enter the Exposome

3.1 'Discovery' of the Exposome

In 2005, molecular epidemiologist Christopher Wild coined the term 'exposome' in an editorial in the influential journal *Cancer Epidemiology, Biomarkers & Prevention*. Wild noted that 'mega-cohort' studies and biobank initiatives marked a subtle shift of genomics away from the clinic and towards the realm of population health, and heralded this as a potentially important development for epidemiology and public health. Yet, he maintained, if science continues to invest heavily in assessing genetic matrices without *also* making parallel investments in capturing environmental exposures, an important opportunity to understand disease processes would be squandered. Wild argued for the development of tools to measure the exposome that were as sensitive as those used to characterize the genome. For him, the 'exposome' is an omnibus concept, encompassing all 'life-course environmental exposures (including lifestyle factors), from the prenatal period onwards.' In these terms, the exposome would include not only exposures in the ambient environment (such as chemical contaminants and environmental pollutants), but exposures that are partly reflective of individual behaviours (such as diet and exercise), as well as molecularized internal markers of exposure (such as metabolic byproducts, circulating endogenous hormones, and gut microflora (Wild 2005)).

Wild's call has been taken up by scientists in various disciplines. In 2010, environmental health scientist Stephen M. Rappaport and toxicologist Martyn T. Smith put forward their own definition of the exposome as being 'the record of all exposures both internal and external that people receive throughout their lifetime' (Rappaport et al. 2010). They reasoned that two opposing approaches could be taken to measure it: a bottom-up approach, which would begin by measuring all external exposures that a person was subject to, or a top-down approach, which would measure internal markers of exposures. They express a strong preference for the top-down approach, arguing that although the bottom-up approach holds great intuitive appeal insofar as it relates 'important exposures to the air, water, or diet, it would *require enormous effort* and would miss essential components of the internal chemical environment due to such factors as gender, obesity, inflammation, and stress' (Rappaport et al. 2010, emphasis added). This statement is telling partly because it displays a marked aversion for assessing environmental exposures in the messy and complicated real world and the preference for taking a downstream approach that documents biological changes caused by exposures after the changes have occurred.

Wild, meanwhile, further (2012) expanded his concept of the exposome by enumerating the broad categories of exposures that could comprise the exposome, dividing it into three realms of inquiry. First, the 'internal environment' includes measurable biomarkers and metabolic and physiologic processes. Second, the 'specific external environment' includes measurable agents of harm such as radiation, chemicals, infectious agents, and lifestyle or occupational exposures; and third, the 'general external environment' as an umbrella term for 'social capital, education, financial status, psychological and mental stress, urban–rural environment, [and] climate' (Wild 2012). Although these levels are potentially useful as a heuristic, the specific things that Wild includes in each suggest that the distinctions across levels are actually much less clear. Some of the factors that Wild lumps into the "specific external exposures" category, for example, are in fact individual behaviours and others are socially mediated phenomena, and others are both. Tobacco consumption is a key example. Wild's model would describe this as a "specific environmental exposure" insofar as it is an individual behaviour, but in our socio-exposome framework, it could be captured at the individual level (e.g., self-report of number of cigarettes smoked per day), at the local level (e.g., anti-smoking ordinances or lack of enforcement thereof), and global level (e.g., national and international trade policies that foster tobacco marketing differently in different locales).

Federal agencies that sponsor research or monitor environmental quality have also recognized the potential for a more expansive definition of environmental exposures. In 2012, the National Research Council of the National Academies (at the request of the National Institute of Environmental Health Sciences [NIEHS] and the Environmental Protection Agency [EPA]) issued a report entitled *Exposure Science in the 21st Century: A Vision and Strategy*. This report pushed the exposome concept further, positing that the individual exposome needed to be understood in the context of an even broader 'eco-exposome,' which should comprise multiple scales of exposure, from molecular systems to individuals, populations, and ecosystems. The report's voluminous array of possible measures includes land-use variables, water quality, food supply, energy use, product consumption, noise exposure, and remote sensing for vegetation cover that could indicate likelihood of pesticide application or indicate climate-induced hazards. Measuring such a broad array of exposures would require leveraging existing sources of data but also the development of sensors, such as smartphone-based sensors, wearable sensors, and nano-level sensors that can detect chemicals, metals, and particulate matter (National Research Council 2012). The eco-exposome is an improvement over the exposome, insofar as it includes exposures that are the end result of social and political-economic forces. Our socio-exposome framework, however, build on the eco-exposome by also accounting for the *underlying social structural components that create and maintain those variables*. For example, measuring exposure to tobacco as the number of cigarettes smoked by an individual in a typical week is insufficient; we also need to account for the regulatory and corporate facets of anti-smoking ordinances and their enforcement, as well as national and international trade policies that foster tobacco marketing differently in different locales.

Initiating a program to operationalize and measure the socio-exposome is urgent because exposomic projects have already been launched, and not all of them have included analysis of the social and political forces that shape the distribution of exposures and influence health. Here we highlight two such projects. First, the Emory Health and Exposome Research Center: Understanding Lifetime Exposures (HERCULES) Project, founded in 2013 with a $4.5 million Environmental Health Science Core Center grant from NIEHS, has oriented its research program primarily towards developing tools to measure 'internal' or 'top-down' exposures. Their research to date has focused on how environmental exposures affect gene expression.[2] Conversely, a consortium of thirteen universities in the European Union have partnered on the Human Life Early Exposome (HELIX) project. They are developing tools to measure the 'specific external' or 'bottom-up' exposures by tracking exposure data on 32,000 women and children from the prenatal period onward, and creating wearable technologies to measure specific exposures in the real world.[3] For example, the HERCULES project has a community outreach core, but their social science activities thus far appear to have been limited to research translation and report-back, not to engaging communities in the front end of the research. Meanwhile, the HELIX project has powerful monitoring and measuring capacities, but is looking mainly at individual rather than community-level exposures. They have begun implementing their bottom-up approach of inventorying exposures, but so far appear to have collected data only on individuals, not on communities. To date, the HELIX project has not matched the extensive data it is accumulating on individual level exposures with the sorts of population- and ecological-level effects that the exposome could potentially encompass.

4. How Insights from Environmental Justice Can Transform the Exposome into the Socio-exposome

The exposome is a potentially revolutionary concept, and one that might push exposure science and environmental public health forward. We have three concerns, however, both about the concept and about the early efforts to assess it empirically. First, although many

[2]http://emoryhercules.com/center-research/research-highlights/, accessed January 6, 2015.
[3]http://www.projecthelix.eu/, accessed December 18, 2014.

early discussions of the exposome-as-concept maintain that it *should* include aspects of the social and political environment, the early projects that have sought to operationalize the exposome have not displayed a serious intent to account for the social and political forces that perpetuate exposures to environmental hazards. Second, and relatedly, early efforts to operationalize the exposome have often ignored the social and political forces that produce the *inequitable distribution* of environmental hazards. Third, the discussion thus far been dominated by academic scientists and regulatory agencies and has largely rejected the necessity and the desirability of lay involvement in science.

For these reasons, we believe the exposure scientists who wish to pursue the exposome concept would benefit from three key insights from scholarship in environmental sociology. First, environmental sociologists and public health historians have documented an abundance of corporate and regulatory practices that perpetuate and even enable the production of environmental hazards. Second, environmental justice scholars and activists have demonstrated that social and political processes result in the *inequitable distribution* of environmental hazards, which unfairly burden low-income communities and communities of color. Finally, sociological research in environmental justice and interdisciplinary scholarship in science and technology studies (STS) have shown that lay involvement in science can improve the quality and execution of environmental health research.

4.1 Corporate and regulatory frameworks

A major limitation of the exposome concept in its current iterations is that it has ignored the ways that corporate practices and regulatory failures are a central factor in perpetuating exposure to environmental toxicants, especially those that affect large segments of the population. Although we agree that the smallest *unit of analysis* in the exposome is an individual, the exposome concept also demands attention to multi-level exposures—phenomena that are ubiquitous or that affect local communities or large populations. There is a wealth of research (from sociologists and public health historians) documenting the many regulatory failures that allow the continued production and widespread dispersal of environmental hazards. Not only do corporations produce, distribute, and dispose of toxic products, but they also often dismiss science on adverse health effects of their products as 'junk science,' or generate reams of contradictory (and sometimes suspect) science to create the appearance of uncertainty. Rather than merely trying to inventory exposures, the exposome could instead contextualize these exposures by understanding the corporate tactics and regulatory complicity that put people at risk of exposure (Link et al. 1995). In effect, this would shift the focus from merely identifying exposures or risk factors and instead help us to understand what puts people at risk of risks.

Importantly, chemical exposure varies across jurisdictions—domestically, nationally, and internationally. Environmental justice scholarship has consistently demonstrated this, whether through closely-observed case studies of particular communities (Taylor (2014); Lerner (2010)) or by studying how power relations between industrialized nations and the global South perpetuate inequalities on a global scale (Pellow (2007); Faber (2008)). What is considered safe in America is not necessarily safe in Europe or Canada. Because regulations vary across jurisdictions, the socio-exposome would require, for example, context-specific information on which chemicals are approved and for what types of uses. It might also gather data on the regulatory regime, i.e., whether regulatory policies are technocratic or democratic, or permissive or precautionary.

The tendency to conceptualize risks or exposures as the byproduct of individual choices and personal responsibility follows broader neoliberal trends not only in the realm of public health but also in public health policymaking arenas and governance practices. Corporate public relations firms have exploited the individualized paradigm of disease causation not only in their marketing materials but also in the corporate science they generate to rebut concerns about the adverse health effects of their products. This tradition began with the American tobacco industry's attempts to undermine claims of public health injury from tobacco smoking (Brandt 2007) and has now become a standard part of the exculpatory rhetoric of polluting industries and the 'merchants of doubt,' who attack any scientific evidence of environmental causation of disease (Oreskes et al. (2010); Davis (2003)). This emphasis on personal responsibility and the instrumental deployment of discourses of doubt about environmental threats serve to obscure the demonstrated relationships between toxic exposures and illness.

In contemporary politics, conservative political opposition consistently sets profit-seeking above regulation, and as a result, government agencies (especially in the United States) have failed to regulate or ban many toxic substances, with the toothless Toxic Substances Control Act of 1976 as the prototypical example. Full toxicity data is available on less than 10% of the more than 80,000 chemicals currently registered for commercial use (Davis et al. 2002). Federal regulatory agencies are limited in their capacity to perform independent testing and must rely on product data provided by the chemical manufacturers; and there is a nearly impossible burden on safety advocates to demonstrate proof of harm before regulatory action may be taken. Because federal regulatory agencies have been so effectively neutered, virtually all successful bans and regulations have been at the state level, and most have been the result of concerted social movement action. Flame retardants are a noteworthy and recent example. In 2003, in response to pressure from scientists, activists, business, and government, the state of California led the nation in banning two major classes of flame retardant chemicals, and nearly 10 other states followed suit. EPA action did not take place until two of those chemicals were no longer in production. And while EPA has touted its success in negotiating voluntary phase-outs with industry, these often happen only if the industry has access to replacement chemicals, which may be very similar in structure and function and which may carry unknown or unpredictable health effects (Cordner et al. 2015).

4.2 Environmental injustices as drivers of the socio-exposome

A second limitation of the exposome concept is that it does not direct attention to the inequitable distribution, production, and disposal of environmental hazards. A rich legacy of environmental justice research has shown widespread inequalities and discrimination in the distribution of all forms of environmental hazards and benefits (Mohai et al. 2009). Like other forms of environmental inequality, what we term 'exposure inequality' is also rampant. In looking at emerging contaminants, we see a clear race and class gradient in exposure to many common hazardous or toxic household products. For example, (Zota et al. 2008) found higher levels of flame retardants in the blood of poor and immigrant people. Certain occupational groups and their families, especially farmworkers, are more heavily exposed to pesticides (Arcury et al. (2002); Harrison (2011)). This is a second critical contribution that environmental justice scholarship could bring to the exposome; unlike the corporate and regulatory failures described above, which may result in nearly ubiquitous exposures or harm to large segments of the population, political inequities often concentrate exposures and disadvantages at local levels or confer risks upon specific groups of people.

Increasingly, environmental health and justice movements have challenged the fragmented approaches that many scientists and regulatory officials take to assessing exposures, and have endorsed the emerging scientific practices we outlined above, arguing that exposure science and chemical policy should be informed by cumulative exposure, windows of development, and community biomonitoring studies (Brody et al. 2014). Because the exposome concept attempts to assess ‘exposure’ as a contingent, compound, and idiosyncratic phenomenon, it has potential to inform efforts to mitigate environmental injustices, but only if metrics, whether they be studies on bio-markers and gene exposure, or measurements of air or water quality, are designed to also look for inequities in exposure.

For these reasons, we argue that the socio-exposome could integrate insights from environmental justice and STS scholarship and productively expand research on the exposome in three ways. First, a study’s framework should account for and be able to measure exposures at very local levels, to take account of place-specific exposures that concentrate hazards in particular communities. Second, the framework should assess not only the inequitable distribution of those hazards but should also document the power inequalities that give rise to them. Third, studies should give affected communities an opportunity to identify contaminants of concern, to formulate research questions that will document them, and to be a part of the deliberations of determining how those findings can be translated into protective policies that will reduce exposures.

4.3 Lay participation in science

Finally, the proponents of the exposome concept have trivialized the ways that citizens can contribute to environmental health science, not only as study subjects wearing sensors that collect data, but as fully informed partners in the research process. We are especially disappointed that one of the earliest articles about the exposome dismissed the question, ‘is there a need for an individual to know their exposome’ as a purely rhetorical one. Wild (2012: 29) rejected the notion that individuals should receive information on things to which they have been exposed:

> in principle, the exposome could be thought of as an accompaniment to the genome to inform personal decisions about lifestyle or medical interventions. However, in terms of public health impact, I do not believe this should be the goal of exposome-orientated research. This is particularly so in the international context, where in many low- and middle-income countries, access to an exposome and the possibility to effect subsequent behavioural or medical interventions will remain constrained for the foreseeable future.

Statements such as this are freighted with multiple problematic assumptions: that information about environmental exposures might only inform ‘personal decisions about lifestyle,’ as opposed to informing policy actions that might reduce exposures or minimize the inequitable distribution of hazards (whether within communities or across nations). This stance also flies in the face of decades of scholarship in environmental sociology and environmental justice, much of which has sought to treat communities as equal partners in the research process and which often assumes an ethical obligation to return results to communities. Finally, it runs counter to a long history of political activism and regulatory actions around community-right-to-know laws, which have been instrumental in helping communities understand what they are exposed to and to press for more protective policies that will protect their health (Wolf 1996).

Over the past two decades, there has been rising interest in and proliferation of lay involvement in science. The citizen science movement has contributed invaluable data about the impact of fracking on air and water quality (Wylie in press.) and the health effects of pesticide drift on agricultural communities (Harrison 2011). The rudimentary tools used by laypeople in these projects, such as bucket brigades to monitor emissions around refineries and petrochemical industrial sites have been well validated and are known to produce high quality data on local exposures (Allen (2008); Ottinger (2013)).

The citizen science movement is closely related to an increased commitment on the part of some researchers to participatory models of research such as Community-Based Participatory Research (CBPR). CBPR is motivated by a belief that researchers have a moral and ethical obligation to engage laypeople in formulating research questions, in collecting and interpreting data, in sharing research results with the community being studied, and in disseminating research findings and discussing how they may be used to inform policy (Israel et al. 2001). CBPR has been especially important in environmental health, and has led to new knowledge of how toxicants affect specific health outcomes. Importantly to our purposes here, CBPR has also drawn attention to social, economic, and political imbalance of power that produce inequities. Over time, this tradition has affected the symbolic and discursive representations of environment used by activists and in the popular imagination. Whereas environmentalists in the 1970s used images of leaking 55-gallon drums to symbolize chemical threats and galvanize people to collective action, contemporary activists have displayed pints of human blood contaminated with persistent organic pollutants to illustrate the pervasive nature of contamination and the extent of toxic trespass (Szasz 1994).

5 Levels, Data, and Measures of the Socio-Exposome

Our socio-exposome framework offers a conceptual scaffolding that assesses exposures across three levels: individual, local, and global. Table 1 illustrates these levels, gives examples of possible exposures, and suggests ways to quantify them (either by collecting new data or by leveraging existing sources of data). As we better understand the properties of these sociomarkers, we will come to understand whether and how they are useful in predicting specific health outcomes. Research in this vein will also need to examine how sociomarkers and biomarkers interact to produce health and illness, in both individuals and larger population groups, from neighbourhoods to nations. Our examples throughout are illustrative rather than exhaustive; moreover, although many of the examples we include are expected to be harmful to health, it is equally important that the socio-exposome framework inventory exposures that are thought to be protective or might enhance resilience.

We place the first level of analysis at the individual subject; although we acknowledge the hazards of oversimplifying complex social phenomena, we agree that research on environmental health should identify whether or not people have, in fact, been exposed to a putative hazard, and characterizing that exposure as precisely as possible. Quantifying these exposures could occur at the molecular level, for example, through gene sequencing studies that would identify variants that increase risk of disease given an exposure, or by searching for epigenetic markers indicating genetic damage, or by identifying the presence of specific toxicants and their metabolic byproducts. Such data need not be exclusively at the molecular scale, however. It could include data on how exposures have affected anatomical systems. It is possible, for example, that some exposures may be more deleterious if the person also has a chronic health condition or a co-infection with a particular pathogen. This information could come from participant self-report, physical exams, or electronic health records. At this level, a mix of cross-sectional and longitudinal data would be optimal, to ensure that we capture exposures relative to critical windows of development (e.g., the periconceptual period, puberty, senescence). Finally, we envision that it will be important to capture data on exposures in an individual's physical or social environment. Exposure scientists have been very inventive at devising biological metrics for certain types of exposures (e.g., how inflammatory markers may reflect exposure to external stressors), but have shown far less creativity in suggesting metrics for capturing evidence of social predictors of those factors. Environmental sociologists can play a significant role in collaboration here. Here again, we recognize (and reject) the DEP's habit of ascribing causal force to individual-level, decontextualized risk factors. Nonetheless, assessment of an individual's social attributes may be informative when embedded in a well-theorized, multi-level causal framework (Krieger (2011); Pescosolido (2006)).

The next level in our framework is the local or community level. The socio-exposome should measure a wide variety of non-biological forces that bear on population health, such as the built environment; the structures and vitality of civil society; government and corporate practices; the political ecology of place; and social determinants of health, all of which materially impact the way that dangerous exposures and poor health are distributed. Data collection at this level could also characterize political power and civic participation, because they have been shown to influence population-level health outcomes. A landmark 1992 study by the sociologist Thomas LaVeist found provocative associations between black political power (as captured by the number or proportion of a city's elected officials from racial minorities) and black infant mortality. LaVeist found that absolute representation was not associated with infant mortality, but that relative participation was, suggesting the futility of tokenism in representation and attesting to the many possible benefits a well-mobilized constituency can have on community health and well-being. For its time, this study was revolutionary in searching for explanations for disparate birth outcomes in political status and representation, rather than confining its focus to indicators of prenatal care, nutrition, or birthweight that are conventionally studied in the biomedical and public health literatures.

At this level, the socio-exposome is especially useful in showing how sociomarkers could be measured with official sources of data, with data freshly collected by scientists, or by civic science initiatives that mobilize citizens to collect data on environmental exposures that would be otherwise unmeasured. With respect to air quality, for example, the U.S. Environmental Protection Agency (EPA) has a network of air quality monitoring stations around the country, but there are not enough, they are not positioned to capture exposures in fenceline communities that may be heavily exposed to a polluting facility, and air sampling protocols do not capture flares or sporadic spikes in exposures. This is an example of where environmental justice activists have applied the principles of CBPR and begun to collect their own data to more accurately portray the environmental burden on their communities, by organizing bucket brigades or by demanding repositioning of EPA sensors in their neighbourhoods (see Loh et al. (2002) and Ottinger (2013)).

The third level in our framework is for global or national forces. This level would capture broad changes in social organization that affect human settlement. To the extent that these forces (e.g., immigration, industrialization, urbanization) affect the ways humans settle in cities, suburbs or rural areas, they will affect the distribution of hazards and resources for mitigating them. Cross-national studies have shown, for example, that budgetary priorities affect population-level health outcomes; a 2003 study documented an association between a nation's investment in defence and military infrastructure and infant mortality (Hyatt 2003). Panel regression analyses of infant mortality in developing nations have shown an interaction between a nation's level of democratic participation and foreign direct investment, enforcement of international lending policies such as structural readjustment, or multinational corporate influence. These forces have more adverse effects on infant mortality in nations at lower levels of democracy than at higher levels of democracy (Shandra et al. 2004). Because these associations have been found, it is important to characterize the different elements of social and physical environments they represent. While this may seem daunting, national and sub-national public health agencies in some jurisdictions have been routinely collecting data on civic participation or inequalities for some time now. England's Public Health Observatories use health inequality indicators as a central feature of their community health profiles (see http://www.lho.org.uk/LHO_TOPICS/NATIONAL_LEAD_AREAS/MARMOT/MARMOTINDICATORS.ASPX). In the United States, the CDC's National Health and Nutrition Health and Examination Survey (NHANES) has gradually incorporated a wider array of social characteristics, such as housing characteristics and consumer behaviour. And in Belo Horizonte, Brazil, the municipal health department gathers data on civic participation, such as the number of newspapers in circulation, the number of cultural events or outlets in the city, or the number of newsstands, bookstores, and stationery shops. Table 5.1 Levels of analysis in the socio-exposome, relevant exposures, and possible data sources

6. Putting the Socio-Exposome into Practice

Studies using the socio-exposome could mimic epidemiologic studies that take the individual as their basic unit of analysis (e.g., a prospective cohort study), or they might study places, communities, or populations that are exposed.

Supposing, for example, that researchers wanted to assess the socio-exposome of a middle-class grandmother in Winnetka, Illinois. They might begin with a physical exam to collect biometric data and blood or tissue samples for molecular assays. They might also administer a survey questionnaire, to gather information about her occupational history, family structure, medical history, and current and past health habits. Suppose that they discover that she had several children and was a former smoker; they would find it important to ask when she initiated smoking, relative to the birth of her first child. The interview could continue by exploring her residential mobility over the course of her life. Suppose they found that she had moved to Winnetka as an adult, but that she had grown up in Gary, Indiana. The research team might recognize that Gary has a large number of polluting industries and toxic dumpsites, and might search for historical or archival data on emissions, to arrive at an estimate (or a proxy) of her exposure to industrial solvents in childhood or puberty. The investigators could merge these data on the woman's individual exam with aggregate data on housing quality, residential segregation, and proximity of environmental amenities such as parks and playgrounds for all of the communities where the woman lived during her life (Steingraber 2008).

Alternatively, we might also illustrate the potential of the socio-exposome approach by canvassing all the ways people might be exposed to a particular contaminant or class of contaminants, such as flame retardants. Over the past two decades, flame retardants have drawn the attention of environmental justice researchers working to characterize household exposures in two communities, on Cape Cod, Massachusetts, and in the San Francisco Bay Area. These CBPR projects engaged community activists to help recruit study participants and collect air and dust samples from their homes, and urine samples from participants on Cape Cod. Analyses showed surprisingly high levels of flame retardants: Cape Cod levels were ten times higher than those reported in European studies, and levels reported in California were 4–10 times higher than those found on Cape Cod. This was perhaps not surprising, since California flammability standards (dating back to 1975) were among the strictest in the country; California's Technical Bulletin 117 required furniture manufacturers to add very high quantities of flame retardants to polyurethane foam used in couches and children's furniture. In response to these localized findings of dangerous exposures in two specific communities, investigators analysed the CDC's NHANES database to demonstrate the ubiquity of exposure in all Americans—these analyses showed that the body burden of California residents was the highest in the nation (Zota et al. 2008). While these local and statewide analyses were unfolding, labor unions representing firefighters became especially concerned about the excessive exposure and disease risk of their members, (especially for breast cancer in women firefighters). They joined forces with environmental health and justice groups, manufacturers, legislators, and scientists to successfully pressure California to revise TB117 in 2014. Because California is such a large market for consumer products in the United States, regulatory standards enacted there are often embraced by other states. The flammability standards originally outlined in TB117 had become de facto national standards, and the revision of TB 117 in 2013 led other states to follow suit. At a global level, the same group of allies and stakeholders defeated numerous proposals by industry to create international flammability standards for candle resistance of television enclosures and other consumer electronics. The International Electrotechnical Commission, the worldwide governing body that sets international standards for consumer electronics, denied industry petitions for new flammability standards four times in six years. Taken collectively, these governance changes could potentially halt the future production of these chemicals, although scientists working in a socio-exposome framework would still need to account for exposure, because these compounds persist in the environment for such a long time. But these examples also show that regulatory standards governing the use of such chemicals are sensitive to pressure by advocates and scientists, so a socio-exposome approach would need to recognize that exposures will vary at different levels of geographic scale. The insights from environmental justice provide a critical reminder that we also need to account for variations among communities in their ability to mobilize, because mobilization can mediate exposure.

As noted previously, federal agencies in both the US and the UK have funded exposome projects (namely, the Hercules and HELIX initiatives). Another newly-launched exposome project avoids the limitations of those other projects and displays real potential to implement a socio-exposome framework. In the U.S., a team at the University of Tennessee Health Sciences Center, in partnership with 9 other institutions, including several historically black colleges and universities, has launched the Public Health Exposome Project (Juarez et al. 2014). It classifies environmental exposures into four domains: natural, built, social, and policy environments. We find this project to be a promising development over some of the other exposome projects underway, because it has a conceptual framework for differentiating between natural, built, social, and physical environments, and thus could become a framework for delineating multiple and complex causal pathways connecting exposures to a specific disease processes and health outcomes. It is also noteworthy that the team has sought to exploit existing sources of administrative and surveillance data, resulting in a massive data set of over 12,000 geocoded variables on 3,141 counties over 30 years (1980–2010). These data can be analysed across levels to detect disease clusters, to examine area-wide risk factors and area-wide contributions to individual risk factors, and to quantify the relative impact of individual, neighbourhood, and societal level exposures. This ‘big data’ approach mimics the merits of the bottom-up exposome approach, without having to collect individual data from scratch on a large cohort and without having to wait for years to accumulate longitudinal data on changes in environmental exposures.

Most importantly, the Public Health Exposome team has included a robust suite of community engagement activities, designed around the principles of CBPR and citizen-science alliances, including a ‘public participatory geographic information system’ that residents can use with minimal training. The public GIS tools allow residents to construct maps of air quality at the county level, for example, or to map tobacco control policies across jurisdictions. By giving community members direct access to the data, they are empowering community members to explore questions about exposures that are of particular concern to them, and to suggest research questions that the team might undertake. The project’s architects view their method as deeply informed by the values and principles of CBPR and directly contributing to environmental justice activism (Juarez et al. 2014). They also have an explicit goal of evaluating the ‘prevention and protection effectiveness’ of existing policies, and hope that their research will lead to predictive models that will better inform progressive and precautionary public health policy and practice. This project appears to be the most progressive of the exposome approaches to date, and aligns most closely with our socio-exposome framework.

7. Conclusion and Directions for Future Research

In this paper, we have described the exposome concept and proffered an alternative formulation of a socio-exposome. The original aim of the exposome is to document all 'life course environmental exposures' (Wild 2005), although this is a monumentally challenging proposition because the environment is multifaceted and constantly changing—as we move from place to place through our lives, and as the places and spaces we occupy are themselves transformed. Expecting that it will be as easy to measure the environment as it has become to measure genes or gene products may thwart efforts to assess complex or frequently-changing exposures. Mirroring exposome research too closely to the path that genomic research has followed also raises the concern that data gleaned from it will, as has happened in the case of the HGP, be used primarily for personalized medicine rather than to achieve broader public health goals (Shostak et al. (2015); Rappaport et al. (2010). This would be unfortunate, as economically marginalized communities without access to healthcare also typically bear the heaviest burden of toxic exposure. This double jeopardy makes it especially unlikely that minority communities will benefit from the highly anticipated wave of "precision medicine initiatives" (Wilson et al. 2014).

It is crucially important that exposure science should include structures of the political economy (not merely isolated political or economic variables or exposures that are the end product of a chain of politically- or economically driven decision making). In this respect, our socio-exposome framework resembles a long tradition of research in medical sociology and social epidemiology that studies the persistence of health inequalities. Our framework, however, differs somewhat from that body of work, because of our close attention to environmental exposures; our focus on environmental justice; and our strong commitment to citizen-science alliances as the preferred vehicle for studying environmental public health. Moreover, we direct our attention to corporate and regulatory practices more closely than health inequalities scholarship typically does (but see Freudenberg (2014)). We need to understand exposures as the end product of actions of institutions and policies of corporate and governmental control. To this end, we have shown how key insights from environmental justice scholarship and action can fruitfully expand the exposome framework, to better account for the social and political forces that produce hazards and which distribute them inequitably. While any new venture that proposes to collect data under the exposome paradigm will need to identify specific exposures of interest and identify the precise mechanisms that shape the production and distribution of those exposures, the socio-exposome framework reminds us that we must also capture the forms of collective action that help communities mitigate, resist, or undo deleterious exposures (Geronimus et al. 2004). Likewise, we believe that by its very nature, the socio-exposome should not remain solely an enterprise of elite academic research. Rather, it should include ways for researchers, funders, policy-makers, community-based organizations, and populations in studied communities to connect with the ongoing research and make use of it in ways that are meaningful to each of them.

How could the socio-exposome fruitfully inform research and policy? At the most basic level, we envision the socio-exposome as a sensitizing concept that helps people, researchers, and organizations to better understand and predict the manifold components of environmental factors in disease. This concept could launch new, more sophisticated research projects, push for more multidisciplinary funding, press for tracking of common exposures, and advocate for progressive and precautionary policies that would mitigate them.

Throughout, we have tried to highlight how existing sources of public health surveillance data could be leveraged to quantify various elements of the socio-exposome. But existing data sets do not necessarily tap all the material we would need, and collecting data on these exposures, which occur at different levels of scale will be challenging. This will require substantial investments in personnel, training, and supporting multidisciplinary research teams to make sense of the data collected. A possible model for such an ambitious undertaking may be found in the National Science Foundation's Long-Term Ecological Research Centers.

As we move forward, we have to be realistic about some challenges. The exposome represents an exciting new frontier for environmental health research, but the advent of new biomedical technologies for measuring the internal and external environment of individuals does not obviate the need to look at the roots of disease through the lens of personal illness narratives (Kleinman 1988) as well as through collective social experience.

In doing so, we must not let method and/or the technique drive the enterprise. It is imperative to maintain – and continually adapt – the balance between technology-driven and conceptually-driven approaches. For example, high-throughput technology may allow for increasing numbers of contaminants at increasing varieties of concentrations, but simple fishing expeditions with massive data sets should not be the driver. Similarly, 'big data' in the social sciences promises similar capacity to enter growing numbers of variables and data points, but that too can be a fishing expedition if not driven by a conceptual model. A continually reflexive evaluation process of socio-exposome research members will need to play a central role to appropriately steer work. Moreover, data needs to be connected to political action. Just having data on environmental exposures is insufficient at effecting social change.

Environmental sociologists have much to contribute to this venture. Many are already working in this vein, to characterize how historical patterns of settlement and migration affect residential segregation and exposure to polluting industries or toxic dumpsites (Downey et al. (2008); Crowder et al. (2010); Pastor et al. (2001); Saha et al. (2005)). Many environmental sociologists are already collaborating productively with environmental health scientists, especially through funding by NIEHS, which has been a leader among the NIH's institutes and centers in embracing CBPR and often requires or recommends integration of social scientists in transdisciplinary teams (Hoover et al. 2015). But there are doubtless many opportunities for new partnerships, which will pose their own challenges. Environmental sociologists will need to address prospective collaborators with definitions and data collection approaches that resonate with each audience. Life and physical scientists who know little about social and political theory or social science research methods may need patience and assistance to grasp the significance of the socio-exposome's non-biological measures, and be persuaded of the feasibility of constructing reliable and valid measures for them. In contrast, scientists who are already sympathetic to this perspective and who have experience in community-based participatory research may have greater capacity to participate in such partnerships. And conversely, environmental sociologists have much to learn about the biological end of environmental health science and about the bio-informatic infrastructure and techniques that are necessary for constructing the complex databases we envision. Environmental sociologists could also contribute by doing ethnographic investigations of the laboratory teams developing exposome research projects, to understand the mental models they are using to approach their work, and to detect the way their assumptions about what constitutes the environment shape or limit the scale of their inquiry.

The work of the socio-exposome, if it is to help the exposome to avoid some of the pitfalls we have identified, must respond to Wild's challenge to measure the environment in a way that is equally as robust as other categories of measurement within the biomedical sciences. Wild's third category of 'general external' influences needs to be carefully unpacked to identify and explore the important non-molecular aspects of exposure. Part of goal three of the 2012–2017 NIEHS Strategic Plan is to 'transform exposure science by enabling consideration of the totality of human exposure' (NIEHS 2012–2017). We contend that this goal can only be met with a broad multidisciplinary response and supportive funding that will allow social science to help define and contribute to both the frontiers and the limits of the exposome and foreground the work of environmental justice.

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Table 5.1

Levels of analysis in the socio-exposome, relevant exposures, and possible data sources

Levels of measurement	Potential Exposures	Possible Data Sources
Individual		
Molecular	Genetic damage, genetic variants, and gene products; toxicants or metabolites that indicate exposure (e.g., plasticizers such as Bisphenol A or MEHP, neurotoxicants such as lead)	Gene sequencing studies; CDC's National Health and Examination Nutrition Survey, or community-oriented biomonitoring projects
Body	Comorbid health conditions, injuries, infections	Physical examinations, participant self-report, health registries, electronic medical records
Social and physical environment	Demographic characteristics (e.g., occupation, poverty, educational attainment, age, race, ethnicity, citizenship) Utilization or participation in health and social services (e.g., faith communities, health services) Health behaviors (e.g., diet, nutrition, tobacco, alcohol) Housing quality at the household level, individual's exposure to traumatic events such as violence	Official sources of data (e.g., U.S. Census Bureau) Population-based survey (e.g., CDC's Behavioral Risk Factor Surveillance System)
Local		
Social environment	Number and quality of health care or human service organizations; Proximity of faith-based organizations or voluntary associations Area-wide poverty; residential segregation	Data from community organizations and federal databases, original research
Physical environment	Housing quality and density, infrastructure capacity for sanitation or pollution control, levels of air pollution, availability of recreational facilities or green space, access to fresh and healthy food	Air quality data (from EPA air monitoring network or bucket brigades)
Political environment	Representation and participation in civic governance; indicators of civic participation such as voter participation	Census data; other official sources
Global		
Government policies	Patterns of economic investment, policing and imprisonment policies, justice systems, history of discrimination and segregation, campaign finance laws	Budgetary priorities (e.g., relative spending on defense or health); State or county-level rankings of community or environmental health (e.g., Robert Wood Johnson Foundations' County Health Rankings, National Conference of Environmental Legislators)
Civil society organizations	Media outlets and organizations; number/strength/influence of lobbying groups;	Data from watchdog groups, government campaign records, antitrust data, surveys on media access, analysis media independence, Encyclopedia

Levels of measurement	Potential Exposures	Possible Data Sources
		of Organizations
Global forces	Immigration, urbanization, industrialization (or industrial decline), climate change, human trafficking, war, pandemic disease	Studies from WHO and other international governance agencies, transnational NGOs such as OXFAM and Greenpeace, Census data showing historical patterns of residential mobility