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# Measuring vapor intrusion: from source science politics to a transdisciplinary approach

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Investigation of indoor air quality has been on the upswing in recent years. In this article, we focus on how the transport of subsurface vapors into indoor air spaces, a process known as 'vapor intrusion', (VI) is defined and addressed. For environmental engineers and physical scientists who specialize in this emerging indoor environmental exposure science, VI is notoriously difficult to characterize, leading the regulatory community to seek improved science-based understandings of VI pathways and exposures. Yet despite the recent growth in VI science and competition between environmental consulting companies, VI studies have largely overlooked the social and political field in which VI problems emerge and are experienced by those at risk. To balance and inform current VI studies, this article explores VI science and policy and develops a critique of what we call 'source science politics'. Drawing inspiration from the creative synthesis of social and environmental science/engineering perspectives, the article offers a transdisciplinary approach to VI that highlights collaboration with social scientists and impacted communities and cultivates epistemic empathy.

**Keywords:** vapor intrusion; indoor air; uncertainty; transdisciplinarity; source science; risk

## Introduction

Contemporary social science investigations and critiques of toxic exposure debates generally seek to explicate the social, political, and environmental dimensions of industrial pollution, techno-scientific reductionism, uncertainty, and the problems, politics, and complexities of chemical exposures and environmental health risks. Social scientists engaged in critical studies of health–environment relations have attended to linkages between political subjectivities and toxics (Brown 2007; Altman et al. 2008; Allen 2003; Petryna 2002; Spears 2014), risk and mitigation politics (Little 2014), and contamination experience and knowledge, expertise, and regulatory gaps (Cohen and Ottinger 2011; Frickel and Vincent 2011). Within this scholarship, there is a sustained effort to show how the sciences used to study environmental issues are deeply social practices with assumptions, power, and politics present at every step of the way and that environmental challenges are social problems that will require societal changes as well as new technologies and scientific practices. A recurring focus of these sociologies and anthropologies of toxics points to how the politics of toxics are actively produced by social, political, economic, and legal processes that condition and steer the science, administration, regulation, and litigation of emerging objects and subjects of environmental risk. Toxic exposure measurements are thus socio-technical artifacts that can become sites of social, political, and scientific struggle and uncertainty (Auyero and Swistun 2008).

This article explores an indoor air exposure known as 'vapor intrusion' (VI). VI occurs when volatile organic compounds (VOCs) that emanate from hazardous waste sites are transported as subsurface vapors in the ground into indoor air spaces. We discuss the emergence of VI as an indoor exposure, showing how the techno-scientific dominance of environmental consulting companies impacts how VI is measured and mitigated. Second, we explore how VI risk debates involve particular problems and uncertainties involved in determinations of the exact 'source' of toxics threat, or what we call 'source science politics', which condition most VI site-specific risk assessments. We explore how the tendency to define and practice VI investigations as source science has political consequences that include disregarding the complexity and ambiguity in assessing VI in the field, obscuring the public health effects and legal contours of VI, and increasing costs to homeowners. Finally, we consider how VI studies, which are currently dominated by a complex mingling of environmental scientists, soil scientists, hydrogeologists, analytical chemists, legal professionals, insurance agents, real estate agents, industrial hygienists, and community relations coordinators (ITRC 2007; USEPA 2015a), can become more collaborative and grounded by an ethos of transdisciplinarity that is informed by *epistemic empathy.* For us, *epistemic empathy* is a necessary step to bridge varying epistemologies or modes of understanding and knowing. Engaging such a concept is especially important for conceptualizing and navigating the uncertainties of environmental public health problems like VI.

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**Constructing vapor intrusion**

In the late 1970s, VI was found to affect indoor air quality at heavily contaminated sites, such as the Love Canal Superfund Site, bringing regulatory attention to this environmental health problem. Despite this early recognition, VI was often overlooked as an environmental health concern in people's homes. Scientists and regulators held that levels of indoor air contamination were not of concern due to processes of dilution and attenuation. Ambiguity about exposure standards (occupational vs. residential) further delayed attention to VI as a threat to homeowner health and safety, in part because hazardous waste cleanup standards were derived using occupational inhalation exposure limits that were so high that they rarely identified VI as a problem in people's homes. Consequently, regulatory agencies that defined non-potable groundwater standards to protect public health against VI exposures using occupational exposure limits made residential VI invisible.

By the 1990s, however, scientists began to document VI in homes. Indoor air sampling at the Redfield Site in Colorado in the late 1990s detected significant levels of VOCs in homes and documented the scientific challenge of variability in VI sampling results (Folkes et al. 2009). To facilitate public education and communication with impacted residents, investigators went door-to-door providing information packets and discussed the program directly with each resident when requesting access for testing. According to one report, testing personnel at the Redfield site were carefully selected, in part, 'for their ability to communicate and work well with the residents' (ITRC 2007, 9). Other community relation efforts at this early VI site included frequent public meetings, periodic mailing of project newsletters, articles published in local community newsletters, door-to-door surveys, and development of a project Web site that made fact sheets and the most recent results of groundwater and indoor air testing available to the public. Ultimately, public agency awareness of the Redfield Site resulted in a national effort to develop protocols among state agencies to better understand the science of VI risk and to revisit sites where cleanup had already occurred but where the potential for VI remained high.

As an environmental public health issue, VI continued to garner increased attention through the 1990s and 2000s. In the early 2000s, the health effects of inhalation of contaminated indoor air resulting from VI were systematically evaluated as an exposure pathway; these analyses showed that VI exposure can lead (depending on the chemical) to asthma, neurological effects, kidney damage, or an increased risk for cancer (USEPA 2002; ADEC 2016). Today, almost every hazardous waste site requires evaluation of the VI pathway and it has been described as one of the top priories at USEPA Superfund Sites nationwide (Manzanilla 2014). Colbert and Palazzo (2008) estimate that one-quarter of all hazardous waste sites in the United States have conditions that could result in VI home exposures, with the most common chemicals of concern for VI investigations including chlorinated hydrocarbons and petroleum hydrocarbons (NRC 2005).

Some VI science and policy advocates have rightfully noted the difficulty of measuring VI exposures, saying: 'Vapor intrusion is difficult to measure because concentrations within buildings vary over time and space, and changes in structures or their ventilation system can open new pathways. Fortunately, once VI is recognized, there are reliable, efficient ways to prevent exposure' (CPEO 2014). While numerous tests show that the mitigation of VI can be effective and relatively inexpensive (USEPA 2015a and USEPA 2008), policy-based mitigation decisions, whether as a precautionary measure or in response to VI characterization results, are still in-the-making as VI evolves as an 'exposure' of concern to state environmental and public health agencies.

In the United States, the USEPA has broad authority to assess and mitigate VI at hazardous waste sites. In June 2015, USEPA released its highly anticipated finalized VI technical guidance (USEPA 2015a). Further, USEPA recently proposed to include VI as part of the hazard ranking system, which is the principal mechanism by which USEPA evaluates sites for placement on the National Priorities List (NPL) of Superfund sites (Federal Register 2016).

Over the past two decades, several institutional actors – federal agencies, scientists, and consulting companies – have come to define and practice VI science as what we call 'source science' in the applied science realm. Much of the regulatory attention to VI aims to trace VI definitively to a subsurface chemical plume and to establish a responsible party's liability for that contamination. Because of the difficulty establishing this liability, most regulatory agencies, including USEPA, encourage a multiple lines of evidence approach to assess VI exposure risks. Such an approach incorporates the interpretation of a wide range of scientific data to make improved decisions at VI sites (USEPA) 2015a). While multiple lines of evidence approaches have shown to be advantageous in addressing technical uncertainties (Pennell et al. 2016), we aim to show that epistemic empathy can extend the definition of VI beyond mere source science complexities to include topics of political and social fields and enrich the application and use of VI science in the field. First, we define the current VI assessment approach, as commonly implemented at hazardous waste sites across the US and highlight an emerging challenge related to trichloroethene (TCE), one of the chemicals most commonly implicated in VI.

Based on the USEPA's current indoor air targets, buildings near groundwater plumes that contain relatively low concentrations of chemicals such as TCE can require reevaluation of the VI pathway. For example, in 2016, Massachusetts Department of Environmental Protection (MassDEP) announced that it would screen 1000 hazardous waste sites to evaluate the potential for TCE exposure risks associated with VI at sites that had been previously considered remediated under earlier standards (MassDEP 2016). Law firms have warned their industrial clients that other states may follow similar trends as MassDEP (Pepper Hamilton 2016).

TCE is an important chemical for VI studies because its use as an industrial solvent has resulted in extensive groundwater and soil contamination (NRC 2005). Additionally, it is still present in some consumer products and therefore can be present in indoor air even in the absence of VI (USEPA 2015b). For almost all other VI exposure risks, long-term chronic exposures are the main concern. However, recently the VI community has been struggling with how to manage TCE exposure risks in indoor air because toxicological studies have shown developmental effects (noncarcinogenic) at very low doses for short durations in susceptible populations. Prenatal exposures that may occur during the first trimester of pregnancy are of particular concern (MassDEP 2014). The short-term exposure concerns associate with TCE creates a new perspective for considering VI exposures.

To date, only a few states have established final guidance about how to manage TCE inhalation acute exposure risks. Management scenarios range from ventilation to evacuation (Manzanilla 2014). Further, regulatory guidance encourages risk management decisions to consider occupant characteristics, for instance, women of child bearing age (Manzanilla 2014). In 2013, after being informed about exposure risks associated with TCE detected in indoor air at Google offices in Mountain View, CA, some women of child-bearing age chose to work from home until concentrations were lowered (CPEO 2014).

Although TCE provides some unique challenges as discussed above, USEPA's approach for VI investigation and assessment guides directs the source science VI approach for most other situations; this approach includes five conditions to establish the presence of VI: (1) subsurface source of vapor-forming chemicals is present; (2) vapors form and have a route along which to migrate (or be transported) toward the building; (3) vapors are able to enter the building through cracks or breaches in the building foundation; (4) one or more vapor-forming chemicals comprising the subsurface vapor source(s) is/are present in the indoor environment; and (5) the building(s) is/are occupied by one or more individuals when the vapor-forming chemical(s) is/are present indoors. Figure 1 depicts the basic conceptual model for VI and illustrates these five conditions.

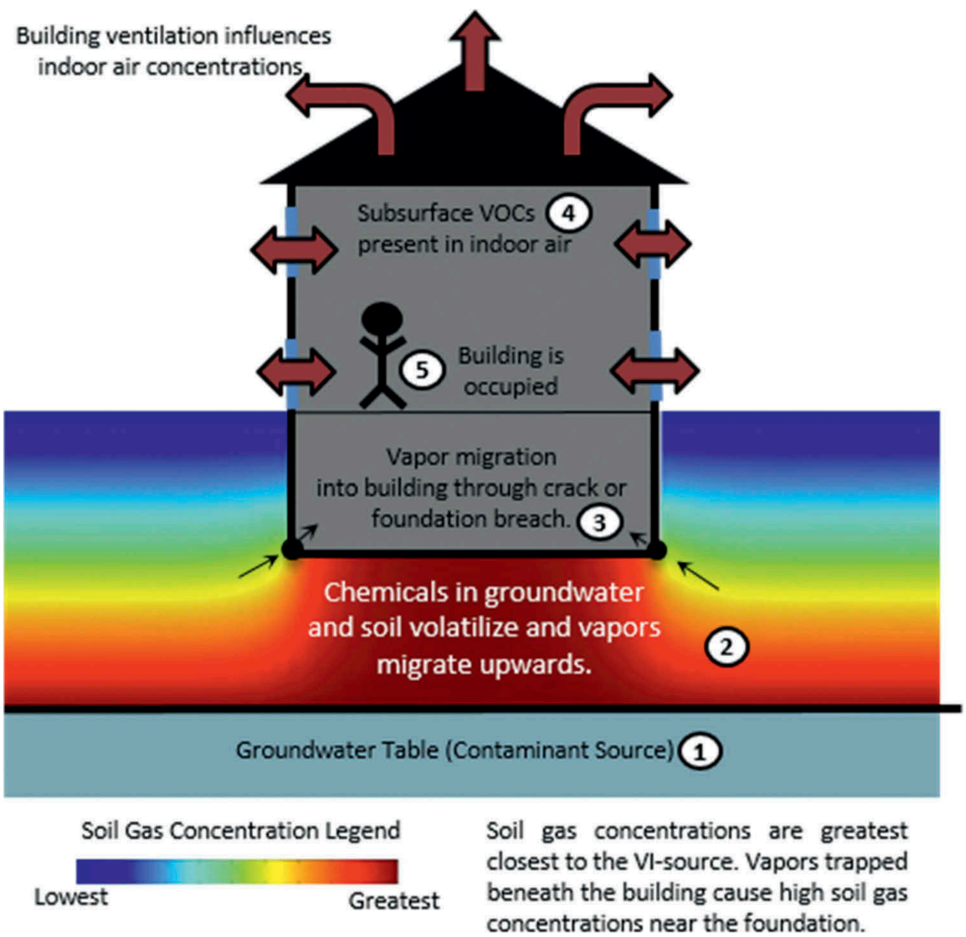


Figure 1. Basic Conceptual Model of VI.

Table 1 provides a summary of the USEPA (2015a) VI assessment approach, which we term a 'source science' approach because it focuses on identifying the source of a particular VI. Although the framework suggests 'involving community', involving community in a VI site requires a wide-angle perspective that attends to not just the 'community' as determined by VI experts, but the community-at-large (Little 2014). Even when 'community' becomes part of the VI site investigation process, the process of meaningfully involving community rarely gets addressed or implemented. For example, the polluter, not the homeowner or occupant, is often the one who hires the consulting company to determine the source of VI, so from the start the site investigation quickly becomes a privatized and individualized form of community involvement whereby homeowners or occupants directly interact with private consultants carrying out the site investigation. Furthermore, homeowner involvement is often overlooked because if regulators have met the five conditions mentioned above, they generally assume that they have met their obligation. Finally, it is worth noting that even homeowners who are not directly affected by VI nevertheless have a stake in remediating VI, especially if the plume is large enough that it could stigmatize the entire community and affect property values. For these reasons, 'community involvement' should not only involve individual homeowners but should also engage the broader community.

Table 1. Summary of the Source Science Approach.

| **VI Source Science Approach*** | |
|---|---|
| • Decide which areas to include in VI investigation<br>• Prioritize multiple buildings and neighborhoods<br>• 'Involve' community<br>• Determine the nature and extent of vapor source<br>• Evaluate vapor migration in soil<br>• Consider the building's susceptibility to VI<br>• Confirm presence of VOCs in subsurface<br>• Confirm presence of non-VI sources (see below) | |
| **NON-VI Chemical Sources often included in VI Assessments** | |
| **Other Sources of VOCs**: Consumer products and preferential pathways (such as sewers) have also been shown in be sources of VOCs during VI investigations. | • Distinguish between VI sources and other chemicals that may be entering the building.<br>• Remove non-VI sources from the building so that the VI investigation is not affected by the presence of these chemicals.<br>• Use advanced analytical techniques and assessment approaches to evaluate the source of chemicals detected in indoor air.<br>• Limited education provided to homeowners about health effects or alternative consumer products. |

*Adapted from USEPA 2015.

Exemplifying this source science approach, VI scholarship focuses on determining whether chemicals present in indoor air originated from a hazardous waste site or other sources (Klisch et al. 2012; McHugh et al. 2011, 2012; Pennell et al. 2016; Guo et al. 2015; Dawson 2016). Motivated by efforts to identify the precise source of chemicals in indoor air during VI investigations, advanced computational models have been developed to estimate VI exposures and inform VI investigations (e.g., Abreu and Johnson 2005; Pennell, Bozkurt, and Suuberg 2009). Likewise, the simpler and widely used model, the Johnson and Ettinger (1991) model, has undergone considerable scientific scrutiny to quantify uncertainty of its VI exposure estimates (e.g., Johnson 2005; Moradi, Tootkaboni, and Pennell 2015). The investment in improving monitoring technologies and the desire to quickly address an estimated 450,000 contaminated nationwide also contribute to framing VI as source science (NIEHS 2014). Despite these technological investments in monitoring tools and models that identify the source of contamination, the US Department of Defense's Environmental Research Programs have invested heavily in research projects to better understand the scientific complexities of the VI process (SERDP-ESTCP 2016). According to Kram (2015), there is 'a huge gap between EPA exposure policy and its position regarding what constitutes acceptable decision-quality data', a situation that further rationalizes the need for continuous monitoring technologies to document sources of VI at a given site or even at sites that have already been remediated. This has led many experts in the VI research or lab science community to advocate for a strengthening in VI studies and expanding source science technology and expertise in VI studies, an effort that has been matched with relatively strong institutional and financial support (SERDP/ESTCP 2016).

The growing awareness and regulation of VI has resulted in the proliferation of actors who have a stake in site assessment and cleanup, including environmental consultants and engineering firms and the legal community. Each of these parties has its own way of responding to the uncertainties and indeterminacies inherent in VI source science. The number of environmental science and technology consulting firms offering sampling, monitoring, mitigation, and remediation services for hazardous waste sites located within or adjacent to communities dealing with VI risk are on the rise (ITRC 2007; MassDEP 2016). Such consultants tout their technical expertise and innovation as a way to capture the market. For instance, one VI consulting company, Geosytec, cites expertise as regulatory negotiators, indoor monitoring experts, mathematical modelers, and pioneers in cutting-edge soil gas sampling techniques (Geosyntec 2015). These environmental consulting companies, made up of an expanding network of techno-scientific experts, are actively informing the 'co-production' (Jasanoff 2004) of VI source science and subsequent cleanup and mitigation efforts.

Such companies also simultaneously help populate and are regulated by the Interstate Technology and Regulatory Council (ITRC) in the United States, placing them in a position to inform regulatory rules that affect assessment and cleanup standards that will govern future practices. The ITRC is a public–private coalition that assists states in the administration and regulation of a range of environmental public health threats, including VI. The organization, though, is largely dominated by consultants and industry representatives. The ITRC and the network of techno-scientific experts and consultants it works with operate in a neoliberal climate of toxics science and governance, meaning that the private or non-profit sectors are expected to respond to public issues that may have been handled by local, state or federal governments in the past (Harvey 2007). Part of positioning the private and civic sectors as the right stakeholders to address social problems is the use of ideas of responsibility. As Gwen Ottinger (2013, 26) writes, 'On the cultural terrain of neoliberalism, experts do not merely reassert their authority on the basis of their mastery and infallibility in technical matters. Rather, they find new grounds for claiming expertise, building their authority on claims to be responsible.' Certainly ITRC's network of VI experts views their science guidelines as good scientific practice that can meaningfully guide VI policy at the state level. But this new form of 'responsible' expertise is developed in a VI science climate that is primarily driven and defined by industry actors, VI scientists, and federal regulators.

## Political consequences of VI as a source science

We argue that while 'source science' that drives VI investigations is invaluable to the experts driving cutting-edge VI research in academic research laboratories because it turns VI into a doable problem, a source science approach directs the investigation towards the determination of source and liability and deflects attention from the social, psychological, and economic impacts of living with VI, even though the complexities and uncertainties of source science are well established and deemed a significant dimension of VI investigations and law suits (USEPA 2015a). As we will show, the tendency to define and practice VI investigations as source science has political consequences that include disregarding the complexity and ambiguity in assessing VI in the field, obscuring the public health effects and legal contours of VI, and increasing costs to homeowners. It also misses no-cost opportunities to promote public health, suffers from the fallacy of techno-scientific reductionism, and overlooks transdisciplinary opportunities to explore the social and environmental complexities of this new toxics debate. In all, VI source science politics create an inequitable relationship between the team investigating VI in the field (i.e., regulatory officials, professional scientists, and the responsible party representatives) and individuals at risk in the impacted community (i.e., homeowners and building occupants) – such inequality has been an enduring question for environmental sociologists.

Although the source science model is appealing because it focuses on identifying the main source and presents what appears to be a straightforward, doable approach, in reality VI science is complex and filled with uncertainty. One of the things complicating VI investigation, for example, is that indoor air quality is affected by *many* exposures in addition to subsurface toxics, such as consumer products and sewer connections (USEPA 2015a). Background concentrations of VOCs (i.e., concentrations that are typically detected in indoor air), have been reported to be near risk-based indoor air targets and in some cases above the regulatory indoor air targets. VI investigations focus so intensely on source science politics, however, that risk communication about these other sources of chemicals in indoor is are typically limited to how those chemicals might 'complicate' the VI characterization process, rather than broader health implications relevant to building occupants. The presence of chemicals in indoor air that originate from consumer products, for example, is often ignored in the hunt for a 'primary source' of VI (USEPA 2011). The inability to account for and communicate about multiple exposures in turn can affect people's health and their ability to take action to remedy or limit exposures. So, while a basic goal of VI science is to create certainty about the source–intrusion relationship, most VI scientists are accustomed to the front-end complexities of just finding reliable techniques to measure, with certainty, VI. In contrast to the way the law, regulatory agencies, and consultants emphasize identifying the source, the current scientific discourse on VI is marked by ambiguity, which contributes to the overall complexity and 'volatility' (Rolph, Torres, and Everett 2012) of both VI science and the existing VI regulatory environment.

Related to this point, the promise of a straightforward source science approach is not held up in the courts. The ambiguities confronted by communities coping with VI risk are also conditioned by the volatile environment of litigation found in many communities of contentious toxics exposure (Little 2014, 2013). According to some environmental law specialists, VI 'has become a hot topic amongst legal practitioners' (Rolph, Torres, Everett 2012, 107). Rolph, Torres and Everett (2012, 107–08) add that '[t]he attention and concern arises largely from the uncertainty surrounding VI – an uncertainty that pervades real estate transactions, contaminated site cleanups, toxic tort suits, and class action litigation.' One lawyer working on VI cases explains that 'The uncertainty about basic scientific and regulatory conclusions is not easy to counsel your clients through' (Distler et al. 2013, 10). It turns out that the environmental regulation and litigation politics informing the complexities of VI risk (e.g., building-by-building exposure variation) reflects a more general challenge of environmental law and regulation. According to Kysler (2010), 'environmental lawmakers and regulators not only must assess and manage threats of an unknown magnitude but they also must do so within the context of numerous overlapping dynamic systems, each of which is characterized by such perplexing features as extreme sensitivity to minor variations in condition, [and] irreducible levels of uncertainty' (Kysar 2010, 73). The continued struggle for residents at VI sites who have taken legal action is that relying on the nature and extent of the VI source, potential exposure pathways, human health exposures, and risk data as evidence for their cases is difficult for lawyers to work with. In other words, it is the combination of scientific uncertainty and 'regulatory knowledge gaps' (Frickel and Bess Vincent 2011) that presents an enduring challenge for VI litigations. The promise of source science, in other words, is not realized in residents' struggle for remediation. In these arenas, the uncertainty of VI science is emphasized.

Finally, the search for a primary source also involves invasive practices that can lead to increased costs for building owners. To determine whether VI is responsible for the presence of chemicals in indoor air, practitioners will often sample soil gas vapors from beneath the building foundation or sample outside the building footprint. Installation of these sampling points requires that a contractor drill through the floor of the building and install a semi-permanent sampling point in the floor, which poses a large burden to homeowners. Some home and building owners have found these methods so disruptive that they have refused sampling altogether. This reluctance of homeowners to allow sampling produces knowledge gaps that both hinder site remediation and obstruct research that would permit the development of more sophisticated models of VI. Again, while 'involving community' is part of the EPA's VI model (see Table 1), the ground-level politics of homeowner noncompliance figure in VI site investigations and further complicate even laudable community involvement efforts.

## Transdisciplinarity as a way to strengthen VI analysis

To counter the reductionist practices of VI source science, we propose a transdisciplinary approach that (1) brings social scientists into VI work, (2) includes homeowners and other impacted community members as active participants, and (3) relies on epistemic empathy. Such an approach can redefine how VI is understood and measured, potentially leading to emphasis on complexity, uncertainty, and the community instead of individuals.

First, social scientists need to be part of VI investigations to ensure that the concerns and values of impacted community members – from single-family homeowners to renters at a multifamily residence – are recognized, documented, and folded into VI site characterizations. Current VI management strategies approach 'community' at the level of 'public education and community outreach' (ITRC 2007) and mostly emphasize how good community engagement is achieved by sharing information to impacted 'homeowners' in an efficient and timely fashion. This is a good practice to continue at VI sites, but it falls short of qualifying as good social science. Social sciences are most needed at VI sites because these practitioners have the skills to engage and articulate who the 'impacted' community is, they have systematic methods for identifying and interpreting community concerns, they can assist in science translation and communication, and the social sciences can be used to improve communication among members of the VI scientific team.

Within a neighborhood impacted by VI, for example, the community is comprised of a heterogeneous group of individuals with different values and perspectives, including property owners, building occupants, tenants of single-family homes, tenants of multifamily homes, and business owners. Collectively, these social actors serve as gate keepers within a VI-impacted community. They can both provide and limit access to data collection and VI mitigation, as well as provide institutional knowledge about past, current, and future exposures and place-specific knowledge about neighborhood history in general, and the history of the building in which they live and/or work in particular. Within the techno-scientific-dominated realm of VI 'source science', engaging community decision makers to become more than just gate keepers has been largely undervalued. However, as we recognize the widely documented techno-scientific uncertainty in VI exposure risk assessments, epistemic empathy calls for meaningful social and technical science engagement with communities as a means to improve actual decision making at VI sites; even if that effort confronts its own plethora of complexities, complications, and consequences.

Second, community members need to be part of VI investigations. The USEPA's original definition of VI offers the possibility to imagine a different role for the homeowner or occupant. Returning to the USEPA's VI assessment framework in Table 1, and the USEPA's fifth condition for establishing the VI pathway, which considers the occupant, requires an additional analytical technique that could potentially open up VI studies to multiple lines of evidence and concern for both indoor air studies and social science studies of the human dynamics of VI. USEPA acknowledges the need for community involvement at VI sites and has dedicated an entire section (Section 9) of the finalized guidance to the topic (2015a). Although attention to the community is currently given short shrift, we should think more carefully about why community participation matters. At a minimum, it might encourage some otherwise reluctant homeowners to allow sampling, if they can see that their community is well represented in the investigation process.

VI experts recognize and confront the uncertainty and instability of VI science, which augments the challenge of articulating what the actual environment health risks of VI are. In this way, VI exposes a discursive crux: 'Discursive gaps emerge when there are conditions to deal with for which there is no available idiom, no way of thinking that can grasp what is at hand. Discursive risks emerge because of a tendency to rely on established idioms and ways of thinking, nonetheless' (Fortun 2012, 452). We agree that transdisciplinary projects emphasizing community collaboration 'give communities data to fully comprehend their exposure experience, to pressure government agencies to respond to and remediate environmental harm, and to bring about policy change that is proactive and precautionary to prevent other communities from experiencing similar problems' (Hoover et al. 2015, 1103). It goes beyond handing over the tools of exposure science to impacted communities or simply swapping theories and methods across disciplinary membranes. Instead, it involves active boundary crossing and upholding an ethos of meaningful collaboration.

Finally, as part of the move to democratize VI science we argue that building *epistemic empathy* is a necessary first step. No experts – scientific, social scientific, legal, regulatory, or citizen scientist – can fully grasp the complexities and nuances of VI assessment on their own. We share more than we even know we share. This can become most clear when people from different disciplines and epistemic communities partner and try to think through problems together. Building *epistemic empathy* is more a practice of collaborative thinking and visioning than an approach driven to master or 'solve' VI complexity. It is more a way of recognizing the diverse ecology of experts, from state regulators, environmental engineers, social scientists, PRPs, lawyers, to homeowners, interacting in VI sites. Surely, these social actors navigate VI in converging and diverging ways, but the very knowledge of VI, however incomplete or specialized this knowledge may be, makes all these actors accountable.

Maybe before even grappling with 'knowledge gaps' (Frickel and Bess Vincent 2011) and prior to building more sensitive community–science collaborations, we need an additional first step attending to the 'empathy gap'. A transdisciplinary approach to VI studies devoid of epistemic empathy will ultimately interfere with techniques aiming to overcome highly cultured disciplinary and epistemic boundaries (Lee and Wallerstein 2004). As Dewey insisted, 'A term is an object so far as that object is undergoing shaping in a directed act of inquiry' (Rabinow 2003, 13). VI is an evolving 'act of inquiry' calling for a more direct transdisciplinary vision that refuses reductionism in light of actually existing technoscience complexity.

Contemporary environmental public health problems invoke discussion of not just exposure pathway and health outcome complexities, but also complexities of disciplinary boundaries and edges. Both environmental and social science researchers grapple with the challenges and politics of risk production and 'toxic uncertainty' (Auyero and Swistun 2009, 2007). We would argue that VI cases are, like all toxic disasters, 'productive events' (Bond 2013) insofar as they present new exposure science and community engagement challenges. The escalating attention on VI in the regulatory community has, however, created a sense of urgency. There is an 'epistemic urgency of [VI] disasters; that is, how [VI] disasters demand to be thought and the social consequences of how they are thought' (Bond 2013, 707). For example, regulatory reactions to known or possible TCE exposures shapes the 'epistemic urgency' of VI. Given the short-term exposure concerns discussed previously, risk management of TCE exposures require a swift decision time frame – in fact, much quicker than is typical for typical VI exposure risk characterization efforts. Regulators and VI practitioners are being forced to make decisions to protect against exposures before the exact source of the TCE can be identified, a situation that once again highlights the need to attend to toxic source science politics to better understand emerging VI debates.

As mentioned earlier, a primary crux of VI site characterizations is the problem of home access and working directly with homeowners who may be reluctant to provide access to their home for necessary sampling. It calls for an engaged synthesis of environmental engineering/exposure science and environmental social sciences, a synthesis that actively seeks to account for a broader understanding of the 'stock of knowledge actors' at VI sites: 'The stock of knowledge actors have about their hazardous surroundings at a particular time and place is thus the joint product of the history of that place, the routines and interactions of its residents, and the power relations in which they are enmeshed' (Auyero and Swistun 2008, 374–375). A new knowledge actor on the scene in VI sites, as we have shown, is the private VI science consultant who works to produce knowledge for a paying client who is most interested in determining the toxic source to better determine responsible party accountability. As shown in Table 1, exposures risks to chemicals that originate from non-VI sources are only evaluated if they inform VI characterization efforts.

Using a transdisciplinary approach to VI can lead to reframings of both the problem and solutions. Highlighting how communities can be engaged, one well-respected VI expert at the USEPA, for example, recently promoted a 'Soil Gas Safe Communities' approach (Schuver 2013). Schuver suggests that creating a 'Soil Gas Safe Community' designation could be established where a majority of current and new buildings in a community are maintained so that soil vapors do not enter the building. In this way, the buildings in the community would be protected against the many adverse effects of soil gases near building foundations, including moisture, gases from leaky sewers, as well as chemicals such as radon, TCE, and other toxicants associated with VI. Since this designation process would be a community-level effort, the community itself would have to first desire and then seek the designation as a Soil Gas Safe Community (Schuver 2013). While this approach sustains a techno-scientific bias, it is encouraging as a new perspective and technique of community engagement because it substantially deviates from past source science approaches and acknowledges the role of communities in coping and managing their own environmental exposure concerns and experiences in general and their VI burdens in particular.

## Conclusion

Remediating VI sites has, for the most part, been practiced as a deeply applied source science, where most actors are primarily concerned with the technical problem and solutions, for example, focusing on measuring the source of VI with new technologies and methods. In this article, we have argued that the emphasis on source science conceals the public health effects of VI, the increased cost to homeowners, and the complexity and ambiguity of VI science. As noted at a recent conference on environmental health–social science collaborations, many of the most impactful and sustainable forms of collaboration between environmental health scientists and social scientists are those rooted in interdisciplinary collaboration and which include communities in the process of investigating and remediating toxic exposures (Finn 2015; Hoover et al. 2015). The complex nature and politics of VI are not simply born from VI science and policy itself, but by how VI is produced, characterized, thought, and who indeed is brought together to coproduce VI. For this reason, we argue that the VI site characterization process would benefit from more transdisciplinary cooperation.

It is well known among VI professionals that part of what makes VI studies difficult is that regulators and consultants see VI differently and interact with this toxics source and exposure concern differently. Consultants largely focus their attention on the 'client' (e.g., responsible party or homeowner), while state and federal regulators focus on 'standards'. This schism augments the already existing complexities and uncertainties of VI characterizations, and largely ignores the concerns of the homeowners and residents. Studying and governing VI, while critical and complementary practices, does not resolve the chronicity of VI complexity and uncertainty for residents coping with this toxics exposure concern and the social and environmental scientists engaged in VI studies. This new field of environmental exposures and toxics source science ought to seek out alternative, transdisciplinary approaches to avoid sloppily reducing a complex issue to a matter of vapor behavior and technologies to detect intruding subsurface gases. Moreover, building more transdisciplinary empathy could help us expose and negotiate gaps in our understandings and misunderstandings of each other as researchers navigating the techno-science complexities and lived conditions of toxic confusion, frustration, and suffering (Auyero and Swistun 2009, 2007; Singer 2011). It is time to embrace the social and political dynamics of emerging VI science and policy and attend to the various knowledge hybrids that *could* and *should* inform critical social and environmental science discussions of this emerging toxics debate.

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