Inspiring Collaboration: The Legacy of Theo Colborn's Transdisciplinary Research on Fracking

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Abstract

This article describes Dr Theo Colborn's legacy of inspiring complementary and synergistic environmental health research and advocacy. Colborn, a founder of endocrine disruption research, also stimulated study of hydraulic fracturing (fracking). In 2014, the United States led the world in oil and gas production, with fifteen million Americans living within one mile of an oil or gas well. Colborn pioneered efforts to understand and control the impacts of this sea change in energy production. In 2005, her research organization *The Endocrine Disruption Exchange* (TEDX) developed a database of chemicals used in natural gas extraction and their health effects. This database stimulated novel scientific and social scientific research and informed advocacy by (1) connecting communities' diverse health impacts to chemicals used in natural gas development, (2) inspiring social science research on open-source software and hardware for citizen science, and (3) posing new scientific questions about the endocrine-disrupting properties of fracking chemicals.

Keywords

fracking, transdisciplinary, environmental health, endocrine disruption, environmental justice, unconventional oil and gas

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Introduction

Dr Theo Colborn, formulator of the endocrine disruption hypothesis, passed away on December 14, 2014 at the age of eighty-seven. Colborn, an inspirational and unlikely scientific figure, started her PhD at the age of fifty, after careers as a pharmacist and sheep farmer in rural Colorado and went on to make major scientific discoveries in her sixties.[1,2] She is credited with first recognizing the systematic potential of synthetic chemicals at low environmentally relevant concentrations to disrupt embryonic development by perturbing hormonal signaling. Further research has shown that such endocrine disruption can play a role in many disorders including ADHD, infertility, obesity, and cancer.[3] Colborn's scientific contributions have been recognized by scientific, environmental, and public interest societies alike. She received many awards, including the International Blue Planet Prize (2000), the Rachel Carson Award from both the Society of Environmental Toxicology and Chemistry's (2003) and the Center for Science in the Public Interest (2004), the TIME Global Environmental Heroes Award (2007), and the National Council on Science and the Environment Lifetime Achievement Award (2007).[4]

Colborn was undoubtedly one of the most influential environmental health scientists in recent history. Recording the story of such a woman is an important project and corrective to the "Great Man" tradition in the historiography of science. This tradition contributes to gender inequity in sciences by silencing and sidelining women's scientific work.[5–8] However, regardless of gender, it is all too easy to fall into the traps of a "Great Man" history by ascribing a researcher's success to their personal genius and inherent exceptional qualities so that their success seems inevitable and their stature unattainable to mere mortals. Such histories stunt our understanding of how science is made, how researchers make their success possible, how they are influenced by their cultural and historical context, and how their science is propelled by a network of collaborators.[5–14,a]

Rather than offer such a history of Colborn, this article describes how she managed to shape science, advocacy, and regulation alike through evolving a novel form of research organization, *The Endocrine Disruption Exchange* (TEDX), whose "sound advocacy" was informed by new and "generative" approaches to data mining that actively connected research and researchers across fields to establish new questions. Through "generative databases," we argue, Colborn managed to pose new research questions that called for, and helped form, new transdisciplinary social and scientific networks.

The unique structure of this article's form and content illustrates and attests to Colborn's ability to forge transdisciplinary collaborations. This article is coauthored by life scientists, a community organizer and a social scientist whose life and career directions changed through interaction with Colborn. Our stories, woven together, both past and future, are the ripple effects of Colborn's influence. Sara Wylie met Colborn though her graduate research in the anthropology of science. Ethnographic research with TEDX inspired Wylie

to evolve new methods for Science and Technology Studies research that aim to collaboratively build forms of science suited to studying and responding to industrially induced hazards. Colborn's work incidentally came to focus on the threat to future generations posed by the developmental toxicity of industrial chemicals. Responding to the politics and influence of the chemical and allied industries on policy and regulation of chemical hazards, Colborn developed modes of advocacy and science that aimed to counter the placement of short-term profit over long-term environmental and human health.

Colborn's research conveyed to both scientists and regulators a need to address the questions she raised immediately through research and regulation to protect future generations. We demonstrate the impact of this approach through an analysis of Colborn's investigations, beginning in her late seventies, into the impacts of chemicals used in unconventional natural gas extraction, particularly hydraulic fracturing (fracking).

Fracking is a method of extracting natural gas or oil from previously inaccessible reserves by injecting large volumes of fluid (million of gallons per well) at high-pressure underground with sufficient force to fracture the geological layer and release trapped oil and/or gas.[16,17] The process came into wide use from 2000 onwards and was bolstered by the passage of the 2005 Energy Policy Act, which exempted fracking from parts of the Safe Drinking Water Act, and thus from federal disclosure and monitoring of chemicals used in fracking.[20] The rapid spread of unconventional oil and gas extraction using fracking produced boom/bust dynamics in communities across the United States, including rapid changes in land values, land use and social structure, and also human health impacts.[19–29] In 2014, the United States led the world in oil and gas production, with fifteen million Americans living within one mile of an oil or gas well.[30,31] The Western Slope of Colorado boomed early due to the region's rich reserves of tight sands natural gas. It was also the home to Colborn and TEDX. This article explores how Colborn and TEDX, located in a rural Colorado mining and ranching community, evolved and enabled new forms of activism, social science and science around fracking.

Generative databases and the formulation of the endocrine disruption hypothesis[17,b]

By Sara Wylie and Kim Schultz (empirical material)

Colborn's interdisciplinary approach to research and TEDX's unique structure emerged organically from her work on endocrine disruption and positioned them to take a novel approach to the emerging issue of fracking. Given Colborn's non-traditional background, it seemed unlikely that Colborn's first job following her PhD, as part of a joint United States and Canadian study evaluating the health of the Great Lakes ecosystem, would lead to the formation of a new scientific field.

Retrospectively, Colborn's position as an outsider and her willingness to cross disciplines to form collaborations proved vital to evolving and substantiating the endocrine disruption hypothesis. After interrogating the data to examine rates of cancer in humans and animals inhabiting this ecosystem, Colborn set aside the contemporary thinking that "Toxic Chemicals = Cancer" and began looking for other explanations for the diversity of illnesses in the region's wildlife. She started looking for connections across illnesses that she had previously dismissed as "accidents" or outliers in the scientific data, stories like the mink sterility due to consuming fish taken from the Great Lakes, the occurrence of female–female nesting pairs of bald eagles, and the wasting of seemingly healthy chicks. She noticed that in each of these cases, the higher order predators at the top of the Great Lakes ecosystem expressed the highest degree of health problems. Colborn compiled thousands of papers across disciplines and species, connecting the dots between wildlife studies in fish, birds and mammals, human epidemiological research, and laboratory studies on toxic chemicals circulating in the Great Lakes.[1,2] Colborn's approach to this research was uniquely "undisciplined" in that she looked broadly across the scientific literature in a manner that a practicing scientist in any single discipline would not have latitude or incentive to do. Interestingly, it was also location-specific, tethered to understanding the particular Great Lakes ecosystem where human industry, from chemical production to agricultural pollution, had introduced a host of industrial chemicals including pesticides, plastics, and polycyclic aromatic hydrocarbons. Reading about these chemicals, she realized that while they occurred at low concentrations in the air and water, many could bioaccumulate in organisms, sticking to fat molecules and thus biomagnify up a food chain so that higher order predators accumulated larger "body burdens" of these chemicals.[1,2]

Looking at laboratory studies on these chemicals, Colborn realized many could be hormonally active. For example, DDT and metabolites can act like an estrogen, and like the plasticizer, p-Nonylphenol could induce estrogen-sensitive breast cancer cells to grow.[32] She found research in mice showing that very small shifts in hormone concentrations during development could produce lifelong biological and behavioral changes.[2] Looking back at the health problems occurring in the Great Lakes system, Colborn realized that they could be the outcome of exposures to endocrine-active compounds present in the environment.

New to the fields she investigated, Colborn approached the research in unexpected ways such as setting aside prevailing toxicological paradigms and connecting wildlife, developmental, and cell biology research. This approach produced the endocrine-disruption hypothesis. The database Colborn made in this research became the foundation of TEDX, colloquially called "Monster" within the organization. Colborn and TEDX built a unique niche in the field acting as a hub between scientists, policy makers, and advocacy organizations. Anthropologist of science Kim Fortun examined the shift in

environmentalism to informated environmentalism in the 1990s where environmental organizations embraced research through online databases as a means of grounding their advocacy.[33] TEDX performs a mode of informated environmentalism by building databases that shape both advocacy and research. They analyze these databases to raise new hypotheses and identify holes in the literature. Colborn used Monster to generate new maps of research fields that create new connections such as that the health effects in offspring of higher order predators might be due to their shared exposure to bioaccumlated hormonally active chemicals. Additionally, she employed her databases to generatively connect people across fields of influence from developmental biology to wildlife biology, from basic research to exposed communities.

Colborn's finding might have gone unnoticed, had she simply reported her findings in a publication. However, she recognized the urgent need to address this as a human and environmental health problem and knew that as a junior figure in her own field she needed established experts to corroborate and share her concern. The Wingspread Conference she organized in 1990 put endocrine disruption on the map. She invited all the researchers whose work she had drawn upon: wildlife, cell and developmental biologists, and epidemiologists to learn and examine for themselves the connections she had made across their research. By the end of the conference, the participants, from sixteen different disciplines, shared a new conviction that many industrial chemicals could be producing hormonally induced abnormalities in humans and other animals.[3] This core group of researchers became foundational to the emerging field. They cowrote a book that brought together their research and a consensus statement collectively expressing this new shared concern about the overlooked hormonal activity of chemicals.[34] This strength of using databases of the scientific literature to connect research and researchers across fields proved similarly vital in forming TEDX which, by virtue of its position between advocacy and science, helped build consensus in the field of endocrine disruption and ensure the field evolved in response to emergent questions and research findings.

TEDX and developing an infrastructure for "sound advocacy"

Colborn started TEDX in 2003 with a mission to:

> Gather, organize, and interpret scientific research relevant to chemicals called endocrine disruptors … TEDX's goal is to prevent exposure to and to reduce the production and use of endocrine disruptors. TEDX's strategy to achieve this goal is to provide customized scientific information to academicians, policymakers, government employees, community-based groups, health-affected organizations, physicians, the media and concerned citizens. TEDX's role is to assure the integrity of the science behind the endocrine disruption movement and to provide the foundation for *sound advocacy* (emphasis added).[35]

TEDX's mission statement establishes it as a "boundary organization" between different actors in the field of endocrine disruption, from academics to agencies, nonprofits and the media.[36–39,c] Colborn's influence as a founder of the field of endocrine disruption helped her organization evolve as a hub connecting the diverse spokes in research, advocacy, and policy. TEDX serves these multiple groups by performing background research that summarizes findings across fields, such as analyzing and summarizing the weight of evidence on contentious endocrine-disrupting chemicals (EDCs), like Bisphenol A. Their summaries provide grounds for advocacy by offering critiques of both the science and the sociology of the science. For instance, at the request of Fredrick Vom Saal in 2005, they used their Monster database to summarize all of the research on developmental impacts of low doses of estrogenic plasticizer Bisphenol A.[40] Their Bisphenol A summary found a serious discrepancy in results based on research funding: industry-funded studies were far less likely to find low-dose effects than nonindustry-funded studies.[40] Analysis of this difference led to two further scientific studies looking at how methodology used in industry studies, such as the selection of estrogen-insensitive strains of mice, led to their finding no effects.[41,42] By looking deeply at the methods employed to shape research findings, TEDX responded both to the research findings and the social power relationships shaping scientific outcomes. Their research helped ensure the "credibility" of advocates' work by giving them an analysis of the state of the science that was both systematic, examining all the relevant studies, but also strategic, examining the funding, study design, and possible bias of studies that is vital to interpreting science in contested fields.[d]

Thus, TEDX's structure and its concept of "sound advocacy" is a response to the politicization of EDC research. The adjective "sound" is more commonly attached to science in the phrase *sound science*. *Sound science* is a public relations term evolved by tobacco industry public relationships strategists to maintain doubt about the link between smoking and cancer by forcing exhaustive weight-of-evidence studies that over-emphasize outlying data.[43] Since then, the term *sound science* has been frequently used by polluting industries to critique research which raises questions about the health and safety of their products.[e] Under the second Bush administration, it was used to justify and require agencies to study issues ad infinitum before acting, thereby ensuring that rapid responses to environmental health threats were nearly impossible.[51] TEDX is an institutional response to such intense pressures. It provides scientists, advocates, and politicians with not just weight-of-evidence examinations demanded by *sound science* critiques but also weight-of-evidence reviews where the research findings are themselves weighted by a deep review of a study's materials, methods, funding, and potential bias.[52] Providing this depth and breadth of evidence, TEDX supports advocates and politicians against accusations of cherry picking. It also provides scientists with expertise in particular fields with findings relevant to their work but outside of their normal professional circles.

Beyond tactically responding to industry influence in science and politics, TEDX's in-depth reviews made novel connections across data stranded in different fields. For instance, seeking to connect research on EDCs and human development with research in animal models, TEDX released Critical Windows of Development, an online searchable database of all the research on low-dose effects of EDCs on different organ systems across species.[53] Such reviews could help to close scientific debate by showing when sufficient evidence had amassed to warrant action. For instance, TEDX reviewed evidence for non-monotonic dose response relationships in EDCs and concluded the weight of evidence warranted regulatory action.[54] This kind of in-depth review is not rewarded in traditional university-based research, which prizes novel findings over synthetic work. While academic researchers might occasionally publish summaries of research in a field, an academic scientist could not receive tenure for publishing only TEDX style weight-of-evidence studies. TEDX developed and maintained an interesting boundary position both inside and outside the formal academy; it is recognized by, but not part of, the formal academy. Colborn was a professor at University of Florida, but TEDX is not formally affiliated with an academic institution. Additionally, publishing peer-reviewed studies maintains TEDX's academic relevance without forcing them to adopt the academy's reward structure that privileges novel primary research and tends to force specialization in a single field. Further, researchers across the field could non-competitively collaborate with TEDX, as it is not geared to do primary research that would potentially scoop basic academic research. It could, therefore, promote the formation of collaborations among diverse researchers in the field from those looking at flame-retardants in dust to those working on pesticides and mechanisms for EDCs. Thus, TEDX created a space beyond the pressures of academy for scientists and policy makers to reflect on the state of the field. By forging connections actively across disciplines in the field, it helped draw the field into consensus. This role is an important response to the public relations tactic of thwarting scientific consensus by funding and promoting oppositional research intended to perpetuate contention, such as occurred around low-dose effects by using estrogen-insensitive animals in whom low-dose effects would be masked.

Beyond assisting with consensus formation within the field, TEDX's boundary position between communities, advocates, and researchers helped advance the field by connecting research and action to keep research tuned to emerging health hazards. Environmental health hazards such as EDCs have emergent properties that cannot necessarily be predicted in labs, particularly when information on chemical compositions are protected by trade secrets. Researchers frequently have to discover information that is well known to companies. For instance, Tufts researchers had to reverse engineer the components of Corning's plastic tubes to discover the estrogenic element because the company refused to disclose the tubes' composition.[55] Advocate groups are better placed and trained than scientists to respond to problems such as arguing for

corporate transparency. Additionally, substitutes for contentious chemicals like Bisphenol A may come into circulation in products promoted to be free of the potential hazard without thorough testing of substitutes.[32,55] These substitute products raise questions for exposed communities that they need researchers to answer. By networking across advocates/communities and scientists, TEDX helps keep the groups in productive conversation, so researchers stay tuned to the needs of communities and advocates and vice versa. For instance, when TEDX began looking at fracking, they stimulated new basic research in laboratories on EDCs in fracking fluids. By interpreting and communicating the state of the science, TEDX enabled advocates to more readily take up current research to argue for changes in funding and regulation. TEDX published a list of endocrine-disrupting pesticides that informed the advocacy organization, Beyond Pesticides, efforts that have pushed EPA to regulate twenty-seven pesticides identified by Colborn's database and that are already regulated by the European Union as recognized or suspected EDCs.[f] TEDX is therefore positioned to help the field retain coherence between research and action while collectively evolving to respond to new scientific findings and social conditions.

Other contested scientific fields such as climate change and nanotechnology could learn from TEDX's example by building similar boundary research organizations that support the formation of consensus in the field, as well as actively synchronizing research and advocacy.

TEDX is an infrastructural solution to the scientific and regulatory obstacles created by industries whose social, political, and economic capital outstrip even that of regulators, as well as the complex and emergent scientific and social problems raised by industrial hazards such as EDCs. While only comprised of six individuals, a very large amount of paper and a few computers, TEDX is so effective that for NIEHS:

> TEDX fills in a large gap in public health protection. Drawing upon its computerized databases on endocrine disruption and coordination with researchers in the field of endocrine disruption, TEDX provides the very latest summaries of the state of knowledge and its meaning for human health and the environment.[59,60]

The following sections illustrate how TEDX's structure for developing sound advocacy, along with Colborn's method of generative databasing, helped call attention to, and began filling, the gap in public health protections from the hazards of unconventional gas and oil development.

Stimulating debate: The health effects of chemicals used in natural gas development

TEDX's mission veered from endocrine disruptors when Colborn received a call from Laura Amos, a resident of Garfield County, Colorado. In 2001, Amos'

water well exploded at the same time that the major oil and gas company Encana fracked four wells one thousand feet from her home. Two years later, she was diagnosed with a rare adrenal tumor, and both the tumor and her adrenal gland were removed. Concerned about her and her daughters' health, Amos read up on the hazards associated with fracking and came across a memo to the Forest Service written by Colborn about the chemical 2-butoxyethanol (2-BE) used in fracking. As Colborn described, 2-BE can cause adrenal gland tumors as well as damage to organs like the kidneys or liver and can adversely affect the cardiovascular and endocrine systems, among others.[23] Shocked by this potential link, Amos phoned Colborn.

Hearing Amos' story convinced Colborn of the need to connect the community members who felt their health was impacted by unconventional oil and gas development to the research on the chemicals used in their neighborhoods. Collaborating with Earthworks' Oil and Gas Accountability Project (OGAP), which had gathered material safety data sheets for products used to drill the San Juan Basin in southwestern Colorado and northern New Mexico, TEDX began the first database of chemicals used in drilling and their health effects.

At that time, the oil and gas industry claimed only to use soap, water, and guar gum to drill and fracture wells, but the product data sheets showed additional chemicals were used, many that could be toxic to humans and wildlife. TEDX's database helped change the national discourse around fracking by articulating the potential aggregate risk posed to human health by chemicals used in gas extraction. Assembling and synthesizing the research in this new database illustrated that drilling and fracking involved a medley of chemicals linked to a diverse range of human health impacts and revealed the paucity of available data on the chemicals and their health effects.

The database gave the first overview of the health and ecological risk from exposure to chemicals used during oil and natural gas operations. In 2006, TEDX began providing summaries of the hazards of chemicals used in particular locations and in 2011 published the entire database of products known to be used in the United States online along with a peer-reviewed paper: "Natural Gas Operations from a Public Health Perspective."[61] It became a key resource for individuals and community groups concerned with possible health risks that can accompany natural gas extraction, and as of February 2016, it had been cited in more than 250 journal articles, reports, and Web sites.[62] It changed the conversation on the safety of oil and gas well development by providing the first comprehensive review on the potential health effects of chemical ingredients used in natural gas development. Searches of government databases and peer-reviewed journal articles provided the health data. The health effects information was split out into fourteen health categories representing target organs or systems. Of the total 353 chemicals analyzed, 75% of chemicals could affect the sensory organs, such as the eyes or skin, and the respiratory system. More than 50% of

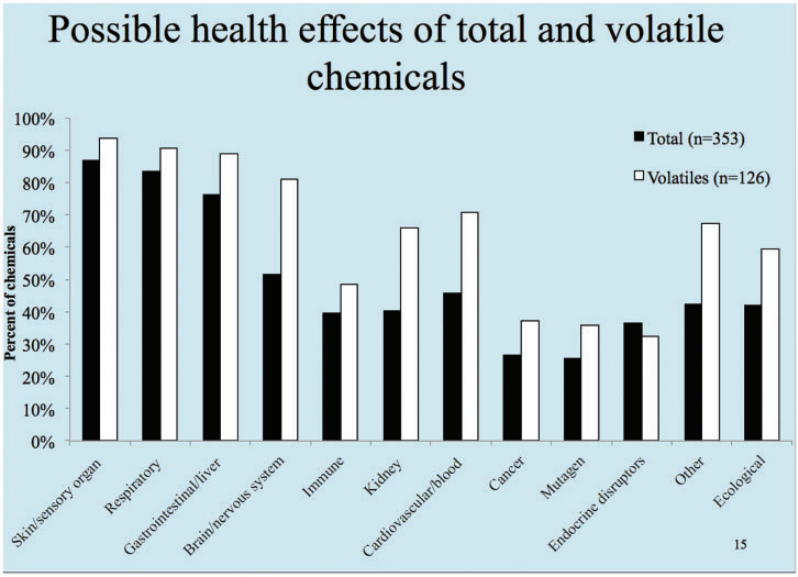

Figure 1. TEDX profile of fracturing chemical toxicity (2011).[61]

chemicals could affect the brain and nervous system.[61] More than 80% of the volatile chemicals were linked to disorders of the nervous system (see Figure 1).

TEDX's database looked at the practice of gas drilling in aggregate rather than by picking out the worst offenders. This approach was immediately useful for communities, as it more readily approximated the consequences of actual exposures to complex mixtures of chemicals involved in the practice. Showing that chemicals potentially evaporating from waste water pits could be linked to a range of health effects from rashes to kidney and nervous system problems gave impacted communities a way to potentially link the diversity of health impacts emerging in oil and gas communities. The primary health impacts that TEDX's database predicted from its summary of scientific research mirrored the symptoms experienced by humans and animals living near oil and gas operations, described in detail by recent health studies: rashes, coughing and wheezing, dizziness, headaches, and nausea.[23–28] The database therefore became a map for sound proactive advocacy by communities, as the section by Deb Thomas of this article illustrates.

The database also provided grounds for communities and organizations to call for full disclosure of chemicals used in gas extraction. By 2010, TEDX had entered 944 products into their database, containing 632 constituent chemicals. Of those chemicals, only 353 had unique identifiers (CAS numbers) that allowed them to be analyzed for health effects. Their research showed that there was ample cause for further research into the potential health impacts of chemicals

used in fracking. For example, of the 246 products used in Colorado, 86% were linked to between four and fourteen potential health impacts.[63] The database also raised new questions about the endocrine effects of these chemicals, as they found 37% were known or suspected endocrine disruptors.[61] The section by Susan C. Nagel follows how scientific research on this question has evolved. TEDX's database also raised questions about how and why so little data was available on gas drilling chemicals. One of their most striking conclusions was that 43% of the product data sheets disclosed less than 1% of the product's chemical composition. They found only 14% of products used in gas production fully disclosed greater than 95% of their chemical composition.[61] The 279 chemicals TEDX found without CAS numbers could not be connected to health information to guide concerned citizens. Many states and federal agencies have since proposed their own disclosure standards, and FracFocus, a national fracking chemical registry, was established in 2011 by an independent organization as a platform for chemical disclosure by well.[64] However, there is still limited chemical data available for products used outside of the fracking stage of development, and product manufacturers can ask for trade secret protection to allow them to keep the product's ingredients confidential. Recent work on more than one thousand CAS-identified chemicals used in the fracking process found insufficient information existed to assess reproductive and developmental toxicity for 76% of the chemicals, highlighting how much is still unknown about the chemicals used in this process.[65]

The following vignettes from a community organizer, social scientist, and life/physical scientists illustrate in form and content how TEDX's and Colborn's novel methodologies and structure helped change the national debate around fracking by creating a loosely connected transdisciplinary movement to investigate and address potential human and animal health effects from chemicals used in gas extraction.

TEDX's influence on communities and regulators

By Deb Thomas

In 2005, while attending an OGAP People's Summit, in Farmington, New Mexico, I met an amazing woman named Theo Colborn. Dr Colborn was an intriguing figure. Just recovering from eye surgery and by no means a spring chicken, she had more energy and charisma than most people many years her junior. One of the forum activities was a bus tour through the oil and gas fields in and around Farmington. It was hot, dry, and dusty, yet Dr Colborn was totally engaged and involved with the group of forty people on the bus. As I watched and listened to her presentation, I began to understand the extent of her knowledge and was inspired by her dedication. She was a force to be reckoned with.

A year later the blowout of Windsor Energy's Crosby 25–3 gas well impacted my community. Our family was one of twenty-five who evacuated their homes, leaving livestock and belongings behind for three days until the well could be killed. The Wyoming Department of Environmental Quality (WDEQ) estimated the blowout released 97 tons of VOCs including 11 tons of hazardous air pollutants (two tons of benzene, toluene, ethylbenzene, xylene), 101 tons of methane, and 43 tons of ethane.[66] Toxic chemicals released into the subsurface geology contaminated the shallow and deep drinking water aquifers in the Line Creek drainage, where we live. After ten years, the groundwater contamination in shallow aquifers has naturally attenuated, but toxic contamination of the deeper aquifers continues. Groundwater is still monitored at more than one hundred monitoring wells, twenty-five drinking water wells, six springs and four points on Line Creek. Despite the evacuation and highly toxic air emissions during the blowout, weeks passed before the air quality was tested. Although residents repeatedly asked the state to monitor air emissions at the development sites still operating, none has been conducted.

Similarly, impacted residents repeatedly requested the state provide a list of drilling fluid constituents used at the Crosby well. When we eventually received a partial list of the chemicals, Dr Colborn and TEDX came to our rescue. TEDX evaluated the health effects associated with the forty-two products identified in the drilling fluids. All of the drilling fluid constituents TEDX analyzed had adverse health effects. Although material safety data sheets (MSDS) said that there were no hazardous ingredients, TEDX found that 21% had one to three associated adverse health effects, 79% had between four and fourteen adverse health effects, and 33% of the products contained one or more potential endocrine disruptors.[67] We finally understood why we were experiencing skin rashes, headaches, respiratory difficulties, kidney disease, and other serious health issues.

Shortly after the blowout, I was called to the Pavillion area to evaluate changes in private water wells that residents feared were linked to oil and gas development. Made up of rural residential development and family farms, Pavillion area residents recognized issues in their drinking water wells and had been requesting help from industry and the State of Wyoming for approximately ten years. Although industry had inadequately answered some concerns, the state had taken no action. Since the state was not providing answers for residents, we requested that the Environmental Protection Agency (EPA) address the water well concerns. In 2008, the EPA began the Pavillion Groundwater Contamination Investigation. Around that same time, we began to recognize that air emissions from the 220 producing wells in EnCana's Pavillion/Muddy Ridge gas field were also impacting residents. The state was asked to conduct air monitoring, but it refused. In late 2009, Pavillion Area Concerned Citizens organized a public meeting to provide information about the potential impacts from the oil and gas development. Community residents, tribal members, interested public, the state and federal regulators, and decision makers were all invited.

Although she could not travel to Pavillion, Dr Colborn agreed to electronically present TEDX's research on oil and gas emissions and potential risks to human health. When we got to our meeting venue, the Pavillion Community Center, we found that no cell service or Internet connection was available. Dr Colborn did not miss a beat; Jennifer Goldman (OGAP) clicked through Dr Colborn's slides as I held a microphone to a landline telephone in the center's kitchen to share her presentation. I will never forget how Dr Colborn's vivid presentation resonated with the impacted people in that room. Community members who had been suffering serious health conditions for years finally had information about what they could be exposed to and how it could relate to their health problems. Dr Colborn had, once again, come to our rescue!

We continued our requests to the state for air monitoring in the Pavillion area. Although the WDEQ placed an ambient air monitor in the area that monitored ozone, it did not evaluate or speciate the VOCs emitted near residents' homes and in the farm fields where they worked.

In November 2011, the EPA released a draft report on their Pavillion area groundwater contamination investigation, linking groundwater contamination to oil and gas development. A breakdown product of 2-BE, a constituent known to be used in fracking fluids, was found in drinking water wells in the study area.[68] As the fracking debate heated up, the EPA findings pushed Pavillion into the national spotlight. Criticism of the draft report from industry and the state also increased. In June 2013, the EPA announced that it would not finalize or seek peer review of its draft report but would instead turn the investigation over to the State of Wyoming (Figure 2).

At that point, the impacted communities in the Bighorn and Wind River basins that I had been working with decided we would band together to do our own air monitoring. We worked with Shale Test to conduct FLIR videography and summa canister air samples; Global Community Monitor and Coming Clean to conduct a bucket brigade, using tedlar bags and formaldehyde badges; Sara Wylie, Northeastern University and Public Lab to conduct monitoring for hydrogen sulfide; Caitlin Kennedy and Evelyn Meisenbacher from Drew University to conduct particulate monitoring, mapping and interviews with community members. Our bucket brigade monitoring resulted in a peer-reviewed article in *Environmental Health* and the Wyoming segment of *Warning Signs; Toxic Air Pollution Identified at Oil and Gas Development Sites* a report of community-based air monitoring in six states.[69,70]

Dr Colborn's impact on me started from the first time we met and continues to this day. She taught me the meaning and value of collaboration. She was a brilliant scientist who knew the horrific problems we face, while still recognizing the beauty of our natural environment. Dr Colborn was charming, kind, genuine, and generous. She was always available to give us support and listen to our theories, no matter how crazy they sounded. She was never constrained by ego or annoyed by our ignorance. Her last words

to me were ''Never stop doing what you're doing and never stop telling your story.'' Theo's inspiration helps me to continue my work with impacted communities in and outside of Wyoming. Along with community members, academics, scientists, and health professionals, we build power through collaboration.

TEDX's influence on agencies

By Sara Wylie. TEDX's work informed and helped stimulate the EPA's Pavillion Area study of water contamination. In response to TEDX's database, the EPA began in 2008 to compile a list of chemicals used in natural gas extraction.[68] Their Pavillion study made use of TEDX's data:

> Additionally, The Endocrine Disruption Exchange (TEDX) has compiled a list of chemicals used in natural gas development in Wyoming. While the TEDX list is comparable to the EPA Study List, it adds several metals that may be found in compounds used in gas well installation and are as follows: aluminum oxide, arsenic, cadmium, copper, iron, lead, mercury, nickel, vanadium and zinc.[68]

The study could be performed under Superfund regulations in part because of the potential presence of chemicals found by TEDX:

> The Superfund Chemical Data Matrix (SCDM) is a list of benchmark values used in the evaluation of National Priorities List (NPL) sites under the Hazard Ranking System (HRS). The following chemicals are found in both the EPA Study List and the TEDX list and have a SCDM associated with them as well.[68]

EPA testing found arsenic, methane, adamantanes, 2-BE phosphate, and caprolactum in the Pavillion area's water. Adamantanes are ''naturally occurring hydrocarbons found in crude and gas condensate.''[68] Their presence points to aquifer contamination by gas drilling. The EPA study additionally found that ''[i]t is possible for 2-BE to react with natural occurring phosphates to produce 2-BE phosphate.''[68] EPA evidence that 2-BE and adamantanes contamination derived from gas drilling (there is presently no competing theory for the contamination) would provide the first government-documented case of fracking contaminating water wells.

Recognizing the threat posed by the EPA's study, the oil and gas industry and the state of Wyoming criticized this study severely and members of Congress reportedly harassed EPA staff in support of the oil and gas industry[71] This pressure, along with budget cuts, reportedly led to the EPA's 2013 decision not to finalize their draft report and instead hand over the investigation to WDEQ. WDEQ's study was to be funded directly by Encana, the company accused of contaminating the aquifer in the first place[71]

Hazardous Chemicals in Drilling Fluids with a SCDM Value

Chemical Name	SCDM – Drinking Water (1/28/2004) Concentration in ug/L (MCL)
Benzene	5.0
Toluene	1,000
Ethyl benzene	700
Xylene	10,000
Naphthalene	20
1-Methylnapthalene	20
2- Methylnapthalene	150
Fluorenes	1500
Ethylene glycol	73,000
Formic acid	73,000
Methanol	18,250
Ethylene glycol monobutyl ether	18,000
Aluminum oxide	36,000
Arsenic	0.057
Cadmium	5
Copper	1,300
Hydrogen sulfide	10
Iron	11,000
Lead	15
Mercury	0.63
Nickel	730
Vanadium	36
Zinc	11,000

MCL Maximum Contaminant Level (US EPA Drinking Water Regulations)

Figure 2. Hazardous chemicals found in hydraulic drilling fluids, including those identified by TEDX, whose potential presence in drilling fluids helped trigger an EPA investigation into the Pavillion area groundwater.[68]

Since the State of Wyoming was put in control of the investigation, there has been no material progress in terms of identifying or remediating the contamination issues in their groundwater. The state has instead engaged in a cycle of review and further research, moves that stall remediation and drain community organizations. The state took a year to hire new experts to review existing data (already collected and analyzed by the EPA experts). Rather than remediating groundwater and residents' water wells, the state has developed a cistern program where residents receive water from underground cisterns filled from Pavillion's municipal water well system. However,

> there has never been an identification of what the aquifer contamination is, how large the plume or plumes are, or how they're moving through the Pavillion area. No-one can say if or when the contamination will impact other drinking and stock water wells in the Pavillion area; including the Pavillion municipal water wells. (Deborah Thomas, personal communication, 10 February 2015)

A second draft report released in 2011 confirmed the first study's findings but has not led to any significant regulatory change and instead recommended additional study.[72] The EPA's lead researcher continued to push the study and after

leaving the EPA published a peer-reviewed scientific article with colleagues at Stanford University in 2016 that supported the original finding that fracking contaminated Pavillion area ground water.[73,74] This decade-long struggle in the Pavillion area illustrates how industry's superior financial capacity and government influence out-maneuvers its opponents, exhausting the communities with endless research and applying relentless pressure through legislators, lobbyists, and skillful public relations. Forcing yet further studies if it is dissatisfied with findings contrary to commercial interest is the same tactic that industry has used to contest other industrially related hazards: tobacco, endocrine disruption, and climate change research.[75]

These cases underscore the need for proactive social science to study corporate activity and influence on regulatory science, combined with proactive science to support community-based research and advocacy. TEDX's generative databasing gave both the agencies and Thomas' community a foundation for their inquiry. However, as the EPA example shows, without the further development of transdisciplinary grassroots science capable of analyzing both the social and the physical dynamics of industrially related health hazards, those experiencing the worst outcomes will continue to be structurally isolated and left to seek individual solutions. Amos, whose experience sparked TEDX's work, lacked the scientific or legal framework to connect her cancer to her exposure and was forced to settle her case out of court with a non-disclosure agreement.[15] Often the only recourse available to exposed people, such agreements fragment exposed communities further and forestall thorough scientific investigation of industrial hazards. The next two vignettes show how Colborn inspired proactive, transdisciplinary research programs supportive of communities on the frontline of fracking. Through connection with Colborn, both researchers began ongoing, grassroots citizen science projects with Thomas.

TEDX and Proactive Social Science

By Sara Wylie

I first met Colborn as a graduate student at MIT. In training as a historian and anthropologist of science, I found Colborn intriguing as a nontraditional figure in science. Writing my first paper about her discovery of endocrine disruption led to my field work with TEDX helping to develop their database of chemicals used in natural gas extraction. That research transformed my research methods and questions and led me to pursue much more engaged forms of social science research from developing web tools for collaborative research between communities and academics to designing new low-cost tools for citizen science.[15,76–78]

Returning to MIT from my work with TEDX, I found striking the vast asymmetries between the information and technical infrastructure available to oil and gas companies over communities. Locating and extracting oil and gas the

world over have produced globe-spanning information systems. Seismic and satellite imaging, hydraulic fracking, and horizontal drilling required for the extraction of oil and gas reserves are the fruit of long-lasting ties between the oil and gas industry centers of engineering and science. Schlumberger, a leading oil field service company, and British Petroleum (BP), among numerous others, are major sponsors of research at MIT.[17] Schlumberger has its own satellite network and the largest seismic imaging fleet in the world. Data from their seismic surveys are compiled into virtual reality experiences, where extraction of fossil fuel reserves can be simulated. Listening to a presentation from Schlumberger's head of information technology led me to ask, what would an information system designed for communities and researchers concerned about the hazards of extraction look like? The question led me to start a research group called ExtrAct, designing and developing web tools for community monitoring and academic study of the oil and gas industry.[15,76]

It is presently impossible to study this industry in aggregate; there is no national or international network to track a company as large as BP or Encana. Yet, they are some of the largest and most powerful economic and social entities in the world. To properly account for the role of corporations in environmental health, new forms of social science are needed that attend to the material consequences of our industries on people's physical, social, and political lives. My work with TEDX showed me that communities are the front line of changing environmental health conditions and that we need research tools capable of connecting impacted communities to rapidly identify and respond to emerging hazards. I regard the development of such tools as proactive social science, developing new informatics tools that enable new forms of sociality where communities can come to recognize and act upon shared interests and new forms of transdisciplinary research. ExtrAct aimed to begin developing such tools. TEDX inspired one of our databases in particular—WellWatch. WellWatch aimed to create a social and research network across communities impacted by gas development. It was intended to be a site where communities could share experiences and resources, from the health effects they experienced to useful resources and doctors they have worked with. For researchers, it would provide a platform for epidemiology, anthropology, and basic research by revealing emerging trends in self-reported data for further investigation.[76]

Such work is increasingly rewarded in the social sciences. The Society for the Social Study of Science for the first time in 2015 offered a prize for Making and Doing in Science Studies.[79] The society started a new journal titled *Engaging Science Technology and Society*, to create a space for publishing transdisciplinary work.[80] My forthcoming book with Duke University Press describes the need for social sciences to actively design research tools that enable networked grassroots research. As part of this effort, I cofounded an organization, Public Lab,[81] that develops low cost, open source tools for community-based

environmental health research.[77] In 2014, Public Lab was invited to present their community's research at the first White House Maker's Faire. I presented work that Deb Thomas and I had developed: a low-cost way of mapping the neurotoxic gas hydrogen sulfide associated with gas and oil production.[78] My work builds on TEDX's proactive research that empowers communities and raises new scientific questions, and now aims to develop novel platforms and processes for social scientists, scientists. and communities to collaboratively study companies and chemicals from the ground up.[15]

TEDX and the Nagel Lab: EDC potential of hydraulic fracturing

By Susan C. Nagel

I first met Colborn in graduate school and was immediately impressed with her extensive library of research articles on synthetic chemicals' effects on a wide variety of organisms' health. She had distilled the key findings of all of the articles and synthesized huge amounts of information to formulate the endocrine disruption hypothesis. She also sought out many of these publications' authors and spent considerable time with them to understand their science.

Years later, I became aware of TEDX's work summarizing the literature on potential health impacts of oil and gas chemicals that illustrated that 130 of 353 chemicals used in unconventional natural gas extraction were known or suspected EDCs.[61] By this time, I had established my laboratory studying the mechanisms of action of EDCs and the effects on adult disease following exposure during development. Although limited research had been conducted on potential EDCs used in fracking, a wide array of chemicals and compounds were reportedly used and liberated throughout the process,[68,73,82–86] and unconventional oil and gas operations had been shown to sometimes contaminate surface and ground water with these chemicals.[73,82–86] Potential health effects from exposure to chemicals from this process were largely unknown at that time and have only recently begun to be assessed.[87–89] Due to my lab's expertise and TEDX's initial work, I realized that we were poised to test the hypothesis that oil and gas chemicals could disrupt the endocrine system.[g]

By Chris Kassotis

When I joined Susan Nagel's lab in 2010, I became very interested in this hypothesis and took the lead on this project; the subsequent research formed the basis of my doctoral dissertation. This work consisted of three main components designed to interrogate the endocrine-disrupting potential of unconventional oil and gas operations and possible adverse health effects resulting from exposure. The first phase of this work focused on characterizing the EDC

potential of commonly used hydraulic fracturing chemicals and was achieved via transient transfections of human receptors and response elements into human endometrial cells.[90,91] In cooperation with TEDX, chemicals were selected from publically available lists of chemicals used by industry and narrowed to twenty-four suspected of potential EDC activities and likely used more frequently than others. We characterized agonist and antagonist activities of twenty-four chemicals for the estrogen, androgen, progesterone, glucocorticoid, and thyroid receptors, and found that twenty-one, twenty-one, twelve, ten, and seven chemicals, respectively, antagonized these receptors.[90] Mixtures of these chemicals were also assessed, and the interactions tested against predicted additive responses; if all chemicals work toward a similar mechanism of action, combinations of chemicals at concentrations that individually produce undetectable responses can yield a detectable response.[92] While some of our chemical mixtures behaved in this manner, others exhibited antagonistic (less than additive) or synergistic (greater than additive) responses. Overall, this work demonstrated that fracking chemicals could disrupt hormones in the body and that some mixtures of these chemicals could result in greater than expected responses.

The second phase of this work focused on water quality near unconventional oil and/or gas development. Connected via Colborn with Colorado communities, we focused research in Garfield County, Amos' home county, and have subsequently conducted research with Thomas in Wyoming. Initial work in Garfield County, an extremely dense-drilling region, assessed surface and ground water quality at sites that had experienced spills of fracturing fluids.[91] Notably, the dense-drilling spill sites exhibited significantly greater estrogenic, anti-estrogenic, and anti-androgenic activities when compared to reference sites outside the drilling-dense region. Further work has assessed surface water near a wastewater injection disposal facility in West Virginia and found elevated EDC activity and has found greater estrogen, androgen, progesterone, glucocorticoid, and thyroid receptor antagonism on and downstream from an unconventional oil and gas wastewater injection disposal site.[93] Notably, samples collected immediately upstream and in a nearby reference stream contained minimal or no antagonism for these receptors, and collaborative work with the U.S. Geological Survey confirmed contamination on and downstream of the site by unconventional oil and gas wastewater.[93] More comprehensive sampling has been performed in Garfield County, Colorado, with results still being analyzed, and ongoing sampling efforts continue in various unconventional drilling regions across the U.S. Taken together, these data suggest that oil and gas operations may increase EDCs in both surface and ground water nearby.

Notably, research on water quality in unconventional oil and gas production regions throughout the United States would be more difficult without the assistance of community-based networks on the ground. Identifying landowners within these defined regions who are willing to allow water sampling on their

property can be challenging. Community groups can provide contact information for landowners willing to allow sampling and detailed general local knowledge that may not be available to researchers. While technologies to detect EDCs in water are not readily available for use in the field by these residents, the protocol for sample collection and shipment to our laboratory overnight is very straightforward. We can then process the samples in the laboratory and test them in our assay systems to evaluate endocrine activities.

The next phase of this work thus far assessed adverse health outcomes in C57B1/6 mice following prenatal exposure to a laboratory-created mixture of oil and gas chemicals.[88–90,94] A mixture of common fracking EDCs was provided via drinking water to pregnant dams at concentrations designed to cover environmentally relevant levels. Male and female offspring health was assessed leading up to puberty, throughout pubertal development, and early adulthood. Adverse outcomes included increased body weights, increased organ weights including heart, spleen, and testes, altered serum hormone levels, and decreased sperm counts in males.[90] Many similar outcomes were found in females as well as disrupted ovarian follicle development, all suggesting potential risks to fertility.[94]

Taken together, this work demonstrates the potential for adverse human and animal health effects from exposure to unconventional oil and gas operation chemical mixtures at environmentally relevant exposures. Continuing work aims to assess water quality and potential human and animal exposure to unconventional oil and gas EDCs in drilling regions across the United States and extend our work to understanding the mechanisms of action of these chemicals, that is, how they work to disrupt development and hormone signaling.

Conclusion

Colborn's research bridged communities, academics, and regulators through TEDX's novel structure and produced ripple effects in communities, the life sciences, social sciences and regulatory agencies. TEDX's work stimulated and informed both popular and scientific attention to fracking which has now become a household word. Following discussions with Colborn, Abraham Lustgarten of *ProPublica* began his more than 168-article series on the issue.[95] Hearing TEDX work helped stimulate Josh Fox, the documentarian behind *Gasland*, to begin work on his award-winning two-part movie series.[97] Similar to Susan Nagel, other academic researchers like Michelle Bamberger, learned about the potential health effects of fracking through Colborn's work and began researching the issue.[h] TEDX influenced regulators, from stimulating Representative Henry Waxman's (D-CA) first hearing on the health and safety issues, to informing EPA Region 8's Pavillion watershed investigation. TEDX's database informed New York's Department of Environmental Protection's investigation into fracking.[44] The results of this report combined with very active community organizing in the state (which was also informed by

TEDX), led to New York banning fracking in 2014.[45] Importantly, Colborn presented results from the database in formats equally accessible for communities and advocacy organizations, and for peer-reviewed scientific articles. For communities, their database of oil and gas chemical health effects provided new ground to connect seemingly disparate illnesses such as rashes, kidney problems, and neurological disturbances. It gave them tools for sound advocacy, expressing and articulating their concerns, and showed the need for further research and regulation. For social science, it inspired the evolution of similar forms of engaged social science research targeted to networking communities to better understand the consequences of industries. As this article shows, TEDX fulfilled NIEHS's quote for another new field by systematically articulating and beginning to "fill a large gap in public health protection" around fracking.

Researchers, NGOs, and community organizations in other fields of contested knowledge, such as nanotechnology and climate change, can draw from TEDX and Colborn's example by supporting the formation of similar boundary organizations that practice generative databasing. TEDX's boundary position between the academy, community organizations, and NGOs uniquely position them to help consensus emerge in the field by providing systematic reviews of the state of knowledge as well as helping the field evolve and cohere by non-competitively building connections across a field's diverse scientific disciplines. Such organizations assist in connecting advocacy and research in fields where industrial interests create obstacles to both scientific research and community organizing by keeping each other abreast of emerging developments.

Colborn's attention to location-based and emergent community health concerns created an organization capable of radically shifting gears to investigate a topic initially unrelated to endocrine disruption. TEDX's position outside of the academy in a rural community where the boom in natural gas extraction occurred made these new connections possible. Other fields could similarly benefit from siting research centers in fence-line communities. Additionally, researchers could follow TEDX's example of placing equal emphasis on publishing their research in forms accessible to the academy and communities and share results with communities as well as publishing peer-reviewed papers. This approach, of proactively providing communities with information useful for their own popular epidemiology and advocacy, places building a timely grassroots public health response before advancing formal academic status with peer-reviewed publications. Such "sound advocacy" is necessary in the context of industrial interests' recursive and exhaustive demands for *sound science* in order to stall action and prevent the formation of scientific consensus. By providing immediately useful resources for communities, Colborn exemplified how individuals can develop bridging organizations that can inspire new forms of research and transdisciplinary collaborations to investigate, legitimize, and respond to the complex, lived experiences of industrially produced environmental health problems. While Colborn is undoubtedly a great woman of science, her particular genius

shows not in her ivory tower intellect but in how her enduring commitment to protecting the health of future generations led her to take front line communities' experiences seriously and respond with generative methods of databasing that non-competitively build environmental health knowledge and meaningfully connect research with advocacy and regulation.

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Notes

a. Since the 1970s, critical historians and anthropologists of science have been analyzing and rewriting scientific histories to contextualize science's great minds from reanalyzing the lives of recognized great men such as Galileo[10] and Einstein[9] to offering counter histories that tell the stories of female and other marginalized scientific figures.[7–10] Science and Technology Studies researchers have also theorized the appeal of ahistorical, acultural writing in the sciences as part of forming the science's misogynistic "culture of no-culture."[11–14]

b. Selected material in this paper from Section by Sara Wylie and Kim Schultz, subsection "TEDX and developing an infrastructure for "sound advocacy" and the section by Deb Thomas subsection "TEDX's influence on agencies" can also be found in Wylie's forthcoming book *Shale Gas: Corporate Bodies and Chemical Bonds*. They are reproduced with permission from Duke University Press.

c. In Science and Technology Studies, the term boundary object is used to describe an object or artifact in a social or scientific movement that different participants in a movement project their unique needs and perceptions onto.[36] They may not all agree on the object's meaning or significance but their mutual perception of its value enables them to collectively support its development and overcome differences.[36] Boundary objects thereby serve to support the coherence in movements where there are internal differences, they can act as bridges between competing interests. TEDX is a boundary organization in this sense, it helps build coherence among groups with different but potentially allied interests.[37–39]

d. In doing this, TEDX effectively developed its own form of Science and Technology Studies, critiquing how science is being constructed in industry-funded science to show no effect.
e. Reflecting the broadening field investigating corporate and public histories of science, Historians of Science have recently contributed many detailed and well-documented studies of how growing and protecting markets for products over the latter half of the 20th century involved actively constructing scientific research institutes, funding science in the corporate interest and skillfully manipulating public perceptions through science.[44–50]
f. From Beyond Pesticides: "Pesticides that Disrupt the Endocrine System Still Unregulated by the EPA": "The U.S. Environmental Protection Agency (EPA), in response to an 11 year-old Congressional mandate, published a list of 73 pesticides and related chemicals that it intends to review for endocrine-disrupting effects, once it finalizes its standards for review. EPA's list of 73 pesticides selected for evaluation includes only 29 of the 56 pesticides that are defined as known or suspected endocrine disruptors by the European Union and *Our Stolen Future* author and The Endocrine Disruptor Exchange (TEDX) president, Theo Colborn, Ph.D."[56–58]
g. The U.S. Environmental Protection Agency now maintains a list of approximately 1,000 chemicals used throughout the process, and the vast majority have not been assessed for their ability to act as EDCs. As such, there was and remains a real need to comprehensively assess the endocrine-disrupting activity of the chemicals used and potential resulting health effects in cases of environmental contamination.
h. TEDX hosts an online tribute to Theo where numerous researchers, activists, friends and family have described her influence in their lives. Veterinarian Michelle Bamberger writes:

> I first learned of Theo's work at the same time that I learned of unconventional extraction of oil and gas, and the potential health impacts associated with this process. I first spoke to Theo just after our first paper came out, to ask about her experiences with illness in animals living nearby unconventional operations. That was nearly three years ago. I remember that Theo was excited that a veterinarian was tackling these issues, and she encouraged and advised me to continue on with our research. Her work inspires and motivates us to do just that.[96]

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Deborah Thomas, is a community organizer, and director of Shaletest.org. Deb is a fourth-generation Red Lodge, Montana, native. Deb began organizing people across the Bighorn and Wind River basins of Wyoming in 1999 when an oil and gas rig began operations 600 yards from her home. During her 16 years with Powder River Basin Resource Council, she organized Wyoming communities contaminated by the oil and gas industry. As a director of Shale Test, Deb continues to help people understand how the extractive industry is affecting their air, water, and health.

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Susan Nagel, PhD, is an associate professor of Obstetrics, Gynecology, and Women's Health at the University of Missouri. Nagel received her PhD from the University of Missouri and did postdoctoral training at Duke University. Nagel has researched the potential endocrine-disrupting activity associated with oil and gas extraction since 2010.