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Outcomes of the Halliburton Loophole: Chemicals regulated by the Safe Drinking Water Act in US fracking disclosures, 2014–2021☆

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ABSTRACT

Hydraulic fracturing (fracking) has enabled the United States to lead the world in gas and oil production over the past decade; 17.6 million Americans now live within a mile of an oil or gas well (Czolowski et al., 2017). This major expansion in fossil fuel production is possible in part due to the 2005 Energy Policy Act and its "Halliburton Loophole," which exempts fracking activity from regulation under the Safe Drinking Water Act (SDWA). To begin quantifying the environmental and economic impacts of this loophole, this study undertakes an aggregate analysis of chemicals that would otherwise be regulated by SDWA within FracFocus, an industry-sponsored fracking disclosure database. This paper quantifies the total disclosures and total mass of these chemicals used between 2014 and 2021, examines trends in their use, and investigates which companies most use and supply them. We find that 28 SDWA-regulated chemicals are reported in FracFocus, and 62–73% of all disclosures (depending on year) report at least one SDWA-regulated chemical. Of these, 19,700 disclosures report using SDWA-regulated chemicals in masses that exceed their reportable quantities as defined under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Finally, while the most common direct-supplier category is "company name not reported," Halliburton is the second-most named direct supplier of SWDA regulated chemicals. Halliburton is also the supplier most frequently associated with fracks that use SDWA regulated chemicals. These results show the necessity of a more robust and federally mandated disclosure system and suggest the importance of revisiting exemptions such as the Halliburton Loophole.

1. Introduction and background

Unconventional oil and gas production via hydraulic fracturing (fracking) has propelled US fossil fuel production in the last few decades; the US is now the world's leading producer of oil and gas. In this study, we extend EPA's (2015) systematic analysis of fracking chemicals used between 2011 and 2013 by identifying chemicals that would be regulated under the Safe Drinking Water Act (SDWA) and were used between 2014 and 2021. We also calculate masses used, investigate operators and suppliers using and providing these chemicals, and compare masses used to reportable quantity (RQ) limits defined in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). This analysis is an important first step for subsequent research including exposure assessments and water quality and toxicology studies.

1.1. Fracking and its ecological and human health impacts

Fracking is a method of injecting high-pressure fluids, typically a mixture of water, sand, and chemicals, to extract oil and natural gas trapped in underground rock formations and draw it to the surface through production wells (US EPA, 2015a). 17.6 million Americans now live within a mile of an oil or gas well (Czolowski et al., 2017). However,

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growing evidence associates fracking with a range of negative health outcomes. Studies have linked close residential proximity to fracking wells to increases in hospital utilization, heart failure, risk of preterm birth, congenital heart defects, migraine headaches, fatigue symptoms, and chronic rhinosinusitis (McKenzie et al., 2012; McKenzie et al., 2014; Webb et al., 2014; Jemielita et al., 2015; Casey et al., 2016; Rasmussen et al., 2016; Tustin et al., 2017; McAlexander et al., 2020). Fracking is also an environmental justice issue; oil and gas infrastructure is disproportionately sited in communities of color and low-income areas (Ogneva-Himmelberger and Huang, 2015; Silva et al., 2018; Zwickl, 2019).

While over 1000 different substances have been identified in fracking fluids and wastewater (Zwickl, 2019; Wiseman, 2009), their precise chemical composition is often withheld as proprietary information. Still, many reported additives pose known risks to human and environmental health (Kassotis et al., 2014; Kahrilas et al., 2015; Elliott et al., 2017). Fracking fluids have been shown to contaminate surface water (Burton et al., 2014; Vidic et al., 2013) and groundwater that supplies drinking water (Hall, 2011; Hatzenbuhler and Centner, 2012; Shaffer, 2021; Shamasunder and Morello-Frosch, 2016), including evidence of contamination by chemicals such as methane, benzene, 2-butoxyethanol, and diesel-range organic compounds (Jackson et al., 2013; Llewellyn et al., 2015; Osborn et al., 2011; Drollette et al., 2015; Fontenot et al., 2013; McMahon et al., 2017). Water contamination routes include: leaking wastewater pits or storage tanks, discharge of inadequately treated wastewater, surface spills during transport, pipeline leaks and spills, defective and deteriorating well casings, chemical migration from fractures into shallow aquifers, and decaying or abandoned wells (Burton et al., 2014; Mauter et al., 2014; Ingraffea et al., 2014; Gilmore et al., 2014). To date, no systematic disclosure or monitoring requirements have been imposed on fracking at the federal level.

1.2. The Halliburton Loophole and federal regulation exemptions

Research on fracking's ecological and health impacts has been limited by a series of regulatory exemptions. Currently, fracking is exempted from all or part of: the Clean Water Act (CWA), the Clean Air Act (CAA), the Emergency Planning and Community Right-to-Know Act (EPCRA), and the Resource Conservation and Recovery Act (RCRA), in addition to SDWA and CERCLA (Wiseman, 2009; Hall, 2011; Hatzenbuhler and Centner, 2012; Wylie, 2018; Cupas, 2008).

SDWA, passed in 1974, is the only legislation that contains legally enforceable standards for drinking water at the federal level. It establishes regulation to protect underground sources of drinking water (USDWs), sets requirements for drinking-water treatment, and builds a framework for researching, monitoring, and regulating contaminants (Hall, 2011). This framework encompasses the National Primary Drinking Water Regulations (NPDWR) (US EPA, 2015b), a federally enforceable list of 94 contaminants with Maximum Contaminant Levels (MCLs), and the Drinking Water Safety and Health Advisories (DWSHA) (US EPA, 2015c), a set of non-binding recommendations for 212 chemicals with Reference Doses (RfDs). See supplementary materials for further information on SDWA's chemical regulation process.[1]

In 2005, however, Congress passed the National Energy Policy Act (NEPA), led by then-Vice President and former CEO of Halliburton, Dick Cheney.[2] NEPA contained what is commonly called the Halliburton Loophole, which excludes fracking from the SDWA's Underground Injection Control (UIC) requirements. This exemption allows a range of chemicals regulated by EPA to be legally injected into underground sources of drinking water, without UIC plans or the monitoring and reporting they require. In the absence of federal oversight, it is necessary to find other ways to track the chemical constituents of fracking fluids. This paper aims to quantify a conservative estimate of the aggregate chemical impacts of the Halliburton loophole from 2014 to 2021 based on data published in FracFocus.

1.3. FracFocus and Open-FF

FracFocus is a fracking disclosure database run by the Groundwater Protection Council and the Interstate Oil and Gas Compact Commission. Twenty-three states mandate disclosure through FracFocus; in other oil- and gas-producing states, it remains voluntary.[3] Though FracFocus remains the most complete set of fracking data available, researchers and regulators have critiqued it as an ineffective vehicle for chemical disclosure and analysis because of its inaccessibility and inadequate quality control (Konschnik et al., 2013; Kinchy and Schaffer, 2018; Avidan et al., 2019; U.S. Department of Energy, 2014). To improve accessibility and reliability of FracFocus data, an independent project, Open-FF, uses open-source code to copy FracFocus' data, clean it, and make it available for systematic analysis using Python (Allison, 2022).

In 2015, EPA examined data from FF Version 1.0 for a preliminary sense of fracking chemicals' environmental mobility. However, FF Version 1.0 has significant data quality concerns relative to FF Versions 2.0 and 3.0, and EPA limited their analysis to 35 (out of 1084 total) chemicals reported in at least 10% of wells (US EPA, 2016). Three of these (naphthalene, ethylene glycol, and 1,2,4-trimethylbenzene) overlap with our analysis. A similar study published in 2022 also reviews FracFocus disclosures over 2014–2020 (Hill et al., 2022). However, they primarily analyze unique chemical counts, rather than total mass, and don't address proprietary chemical use.

This study extends EPA's work by using Open-FF data to track fracking disclosures that include chemicals otherwise regulated under SDWA's NPDWR and DWSHA lists.[4] We further contribute an updated mass use analysis since 2015 and analyze operators and suppliers of these chemicals. Finally, we compare disclosed masses to each chemical's RQ under CERCLA, which defines the minimum amount of a hazardous substance that, if released, requires a facility to notify the National Response Center. In other words, an RQ is one way that potentially dangerous releases are legally defined. We do so using Jupyter notebooks and open-source code, ensuring that the analysis is replicable and transparent.

2. Materials and Methods

2.1. FracFocus and Open-FF

We use Version 14 of Open-FF, which downloads bulk data from FracFocus, stores each chemical disclosure as its own record, and

[1] Tens of thousands of chemicals in current use are not yet registered on any chemical list. A chemical's non-regulation does not necessarily reflect its safety, but rather the slow and sometimes political process of defining contaminants for research and enforcement (Shaffer, 2021; Shamasunder and Morello-Frosch, 2016).

[2] The extensive legal contestation over SDWA's regulation of fracking exceeds the bounds of the present paper. For fuller discussion, see (Cupas, 2008) and (Hall, 2011).

[3] States that require mandatory FracFocus reporting: Alabama, Alaska, California, Colorado, Idaho, Kansas, Kentucky, Louisiana, Michigan, Mississippi, Montana, Nebraska, Nevada, North Carolina, North Dakota, Ohio, Oklahoma, Pennsylvania, South Dakota, Tennessee, Texas, Utah, and West Virginia.

[4] We distinguish between "chemical disclosure" and "chemical use." While FracFocus provides information on what oil and gas companies disclose, there are likely many more individual fracking events - and therefore more uses of each chemical - than what is disclosed.

converts this data into .csv files. Open-FF also cleans the data by clarifying chemical identification and trade secret claims through a method similar to EPA protocol (US EPA, 2016) that uses CAS number/Ingredient-name pairs to correct typos, verifies against authoritative sources (the Chemical Abstract Service's SciFinder tool and EPA's CompTox database), and resolves conflicts of identification.[5]

In addition, Open-FF calculates the masses used for individual chemical disclosures by using the mass of the carrier fluid (e.g., water) and the reported percentage of each chemical within the total mass. The percent masses reported in FracFocus are the maximum of a range that manufacturers report; therefore, Open-FF's calculated masses reflect maximum levels. Whenever possible, these mass calculations are corroborated with a FracFocus field called MassIngredient. When required information is not available or is conflicting, the mass is neither calculated nor reported.[6]

Finally, because many FracFocus disclosures use a "systems approach" in which suppliers, trade names, and purposes of chemicals are disaggregated from their chemical names, CAS numbers, and quantities, Open-FF includes an "associated supplier" field that lists the company most frequently named as providing chemicals for a given disclosure.

2.2. Using Open-FF to assess SDWA-regulated chemical use

We combined the NPDWR (94 chemicals) and DWSHA (212 chemicals) lists and searched Open-FF for these chemicals by their CAS number. This search identified 28 unique SDWA-regulated chemicals disclosed in Open-FF. For each of these 28 chemicals, we drew exposure, toxicology, and critical effects data from the federal databases ToxValDB and IRIS. ToxValDB, part of EPA's CompTox Chemicals Dashboard, collates information from peer-reviewed scientific studies on toxicity and dose-response assessments and provides regulatory values and exposure effects (McEachran et al., 2017; Williams et al., 2021; Williams et al., 2017). EPA's IRIS database characterizes risk through a process established by the National Research Council and integrates information on exposure, dose-response, and hazard.[7]

We combined the data from ToxValDB, IRIS, and Open-FF to generate Table 1, which includes each chemical's regulatory values, CASRN, Chemical Name, total usage in FracFocus disclosures over 2014–2021, and health effects. We used a series of Python scripts to analyze the total disclosures reporting SDWA chemicals and the yearly percentage of disclosures that report both SDWA chemicals and proprietary claims. We also analyzed yearly total masses of each of the SDWA-regulated chemicals, trends in mass over time, and mass use in relation to CERCLA-defined RQs. Finally, we analyzed the operators, direct suppliers, and suppliers most associated with each disclosure. For further methods description, see the browsable version of Open-FF in footnote six.

3. Results

3.1. Frequency, health effects, and regulatory values of SDWA-regulated chemical use in FracFocus disclosures

Table 1 shows the 28 SDWA-regulated chemicals disclosed, their CAS numbers, total disclosures and percentage of all FracFocus disclosures, total mass reported, regulatory values (MCL or RfD), critical effects, system effects, and CERCLA RQs.

Ethylene glycol is most frequently disclosed, appearing in 52,674 disclosures (45% of all FracFocus disclosures). Other high-use chemicals include acrylamide (22,065 disclosures), naphthalene (15,377 disclosures), and formaldehyde (14,370 disclosures). 1,4-dioxane is used in 2,747 disclosures. BTEX chemicals (benzene, toluene, ethylbenzene, and xylenes) are often grouped together because they form the particularly hazardous core of diesel fuels. However, they are not necessarily used together: xylene is present in 2,641 disclosures, toluene in 520, ethylbenzene in 1,819, and benzene in 111.

The 28 chemicals have 11 different system effects. The most common impacted systems are the nervous (39%), respiratory (29%), urinary (21%), developmental (18%), and hepatic (18%) systems. For instance, naphthalene (RfD: 0.3 mg/kg/day) is a carcinogen known to affect the nervous and respiratory systems (Gervais et al., 2010). When inhaled, naphthalene can cause liver and kidney damage (Gervais et al., 2010). Acrylamide and ethylene glycol, the next most-used chemicals (RfDs: 0.002 and 2.0 mg/kg/day respectively), impact the nervous and urinary systems. Acrylamide is a carcinogen and neurotoxicant commonly used in industrial processes, paper production, and dyeing (National Cancer Institute, 2017). Ethylene glycol breaks down into toxic compounds within the body that first affect the central nervous system, heart, and then kidneys (National Institute of Occupational Safety and Health, 2021).

1,4-dioxane (RfD: 0.03 mg/kg/day) is a contaminant of emerging concern and probable human carcinogen (Godri Pollitt et al., 2019). Short-term exposure may result in eye, nose, and throat irritation; long-term exposure can cause urinary and hepatic system effects (Wilbur et al., 2012). Found in numerous groundwater sites, 1,4-dioxane is highly mobile in the environment and does not readily biodegrade (Godri Pollitt et al., 2019). Formaldehyde, another common chemical disclosed, is a carcinogen that can cause nausea, throat and eye irritation, and wheezing and coughing when immediately exposed (Agency for Toxic Substances and Disease Registry, 2022). Finally, the BTEX chemicals cumulatively impact the nervous, developmental, urinary, hepatic, and immune systems. Benzene, for instance, is a known carcinogen with an MCL of 0.001 mg/L, equivalent to half a teaspoon of liquid in an Olympic-size swimming pool (Agency for Toxic Substances and Disease Registry, 2007). Short and medium-term exposure can lead to dizziness, nausea, convulsions, confusion, unconsciousness, and even death at high levels; benzene also interrupts the function of red blood cells (Centers for Disease Control and Prevention, 2019).

Fig. 1a shows a Venn diagram of NPDWR, DWSHA, and total chemicals reported in FracFocus. Between 2014 and 2021, 1,240 unique chemicals were disclosed to FracFocus - more than four times the total number of chemicals regulated by SDWA. Of the 306 total chemicals within the NPDWR and DWSHA, 28 - or almost 10% - have been disclosed in fracking operations.

69% of all disclosures use one or more SDWA-regulated chemicals. 31% (36,261 total disclosures) do not report any SDWA-regulated chemical use. Fig. 1b shows that, on average, fracks disclose one or two SDWA chemicals at a time; at most, seven SDWA chemicals are recorded as being used together. Only antimony, styrene, chlorite, and boron were used less than 20 times between 2014 and 2021; the rest were used much more frequently.

[5] CAS numbers are unique numbers assigned by the CAS (or Chemical Abstract Service numbers) division of the American Chemical Society to avoid the confusions of generic or proprietary names.

[6] Open-FF incorporates multiple safeguards to flag and segregate the data errors found throughout FracFocus. For instance, Open-FF reports the calculated mass of a chemical record only when a disclosure meets several criteria: the sum of disclosure percentages is within a small range around 100%, the total base water volume is reported, the carrier records for the water are reliably reported, and the calculated mass is not inconsistent with the FracFocus field "MassIngredient" when it is available and is itself internally consistent. In addition, for this report, we screened all chemicals analyzed for outliers and removed any records that were inconsistent and could possibly bias the results. All curation decisions are available where Open-FF is published (https://codeocean.com/capsule/9423121/tree). A browsable version of Open-FF is available at (https://frackingchemicaldisclosure.wordpress.com/data-navigator/).

[7] We use information from IRIS and ToxValDB to provide context on each chemical's behavior and health effects, but do not attempt a full exposure study.

Table 1
28 SDWA-regulated chemicals disclosed, total disclosures of each chemical and its percentage of all FracFocus diaclosures, total mass reported, regulatory values (MCL or RfD), critical effects, and systems effects, and CERCLA reportable-quantity reportable quantity limits. Antimony, boron, and chlorine dioxide, and chlorine dioxide don’t show calculated mass numbers because their mass data wasn’t sufficiently reliable.

Chemical Name	CAS Number	Number of disclosures	Percent of all disclosures	Number of disclosures with calculable mass	Total calculable mass reported	MCL (mg/L)	RfD (mg/kg/day)	Critical effects	System effects	CERCLA Reportable Quantity
Ethylene glycol	107-21-1	52674	45	46094	250000000		2	kidney toxicity	Urinary	5000
Acrylamide	79-06-1	22065	19	17634	4600000		0.002	nonneoplastic histopathology; Degenerative nerve changes (increased prevalence of "moderate" to "severe" degeneration in tibial nerves)	Nervous	5000
Naphthalene	91-20-3	15377	13	13299	10000000		0.02	reduced mean terminal body weight (males)	Nervous, Respiratory	100
Formaldehyde	50-00-0	14370	12	11009	1800000	5	0.2	Reduced weight gain, histopathology in rats	Gastrointestinal, Urinary	100
1,2,4-Trimethylbenzene	95-63-6	12862	11	10977	2700000		0.01	reduced pain sensitivity in male wistar rats	Developmental, Hematologic, Nervous, Respiratory	
Chlorine dioxide	10049-04-4	8419	7			0.8	0.03	neurodevelopmental effects	Cardiovascular, Developmental, Nervous, Respiratory	
1,4-Dioxane	123-91-1	2747	2	1315	30000		0.03	carcinogen	Hepatic, Nervous, Respiratory, Urinary	100
Xylenes	1330-20-7	2641	2	2189	3600000	10	0.2	reduced body weight, increased mortality	Nervous	100
Ethylbenzene	100-41-4	1819	1	1334	940000	0.3	0.1	liver and kidney toxicity	Developmental, Hepatic, Urinary	1000
Ammonia	7664-41-7	1503	1	1267	550000		0.97	respiratory system	Respiratory	100
1,3,5-Trimethylbenzene	108-67-8	708	0.6	569	63000		0.01	reduced pain sensitivity in male wistar rats	Developmental, Nervous	
Toluene	108-88-3	520	0.44	389	20000		0.08	increased kidney weight	Nervous, Urinary	1000
Chloromethane	74-87-3	461	0.39	218	46		0.0257	nervous system	Nervous	100
Acrylonitrile	107-13-1	373	0.32	335	18000		0.04	testicular effects: reduced sperm counts, seminiferous tubule degeneration	Respiratory	100
Phenol	108-95-2	302	0.26	160	150000		0.3	reduced maternal weight gain	None	1000
Arsenic	7440-38-2	239	0.2	202	590	0.01	0.0003	hyperpigmentation, keratosis and vascular complications	Cardiovascular, Dermal	1
Benzene	71-43-2	111	0.094	101	7500000	0.001	0.004	reduced lymphocyte count	Immune	10
Epichlorohydrin	106-89-8	95	0.081	85	310		0.006	fertility effects	Respiratory	100
Nickel	7440-02-0	84	0.071	81	990	0.1	0.02	reduced body and organ weight		100
Dichloromethane	75-09-2	48	0.041	46	1100		0.006	hepatic effects (hepatic vacuolation, liver foci)	Hepatic	1000
Di(2-ethylhexyl) phthalate	117-81-7	42	0.036	41	1100		0.02	gastrointestinal distress in humans; developmental and reproductive effects in rats and mice	Hepatic	100
1,3-Dichloropropene	542-75-6	32	0.027	29	67000	0.0005	0.03	chronic irritation	Gastrointestinal, Respiratory	100
Cumene	98-82-8	28	0.024	27	720		0.1	increased kidney weight in female rats	Endocrine, Urinary	5000
n-Hexane	110-54-3	22	0.019	4	290		0.06	neuropathy and atrophy of the testes	Nervous	5000
Chlorite	14998-27-7	5	0.0043	5	21000	1		nervous and developmental systems		
Styrene	100-42-5	3	0.0026	3	1500	0.1	0.2	red blood cell and liver effects	Hematologic, Hepatic, Nervous	1000
Antimony	7440-36-0	2	0.0017			0.006	0.0004	longevity, blood glucose, and cholesterol	Hematologic	5000
Boron	7440-42-8	2	0.0017				0.2	decreased fetal weight (developmental)	Developmental	

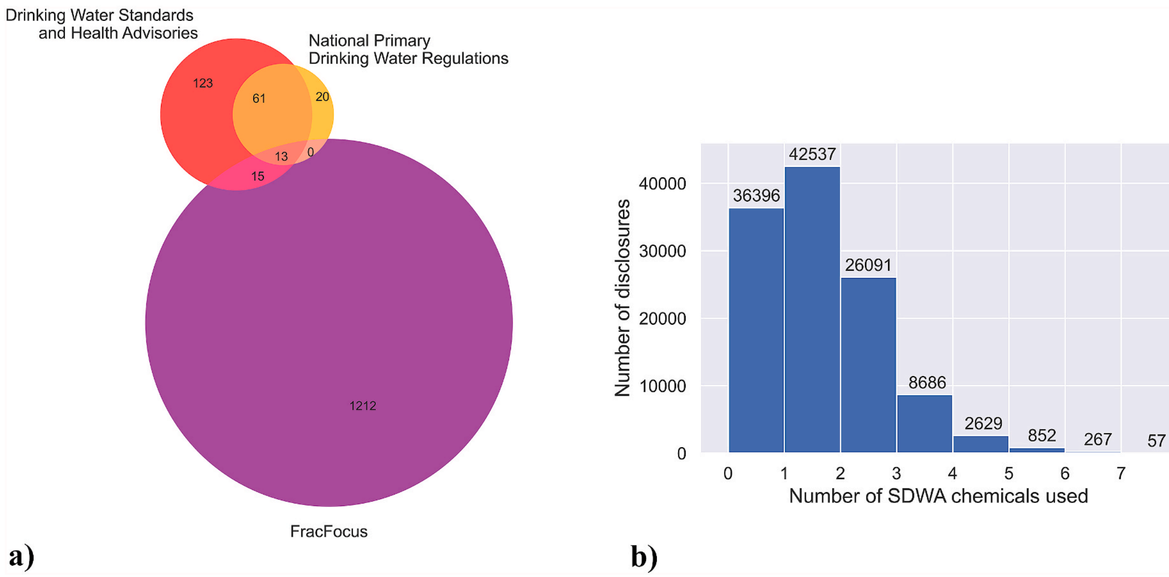

Fig. 1. a: Chemicals listed in SDWA's National Primary Drinking Water Regulations (n = 94); SDWA's Drinking Water Standards and Health Advisories (n = 212) and Open-FF (n = 1240) from 2014–2021. 28 total SDWA-regulated chemicals are disclosed in Open-FF during this period. Figure lb: Number of unique SDWA-regulated chemicals reported per disclosure. Fracks use a median of one chemical per frack; the maximum number of SDWA-regulated chemicals in one frack is seven. Total number of fracks for each column is reported in the number above the column.

3.2. Analyzing percentage of disclosures using SDWA chemicals

Fig. 2a shows the quantity of disclosures per year. The number of disclosures per year varies between 27,652 in 2014 and 7,903 in 2020. 2014 had the maximum number of total disclosures, while 2020 had the least. Specifically, there was a steep decline between 2014 and 2016, with an increase in disclosures from 2016 to 2018. Fig. 2b shows the percentage of disclosures using SDWA-regulated and proprietary chemicals per year. Overall, the percentage of total disclosures using at least one SDWA-regulated chemical remains over 60% regardless of the total number of fracks in a year, though it has decreased from 73% in 2014 to 62% in 2021.

In contrast, disclosures reporting proprietary chemicals have increased from a minimum of 77% in 2015 to a maximum of 88% in 2021. We cannot discern whether SDWA chemicals are being used when disclosures are recorded as proprietary, but the total calculable mass of proprietary chemicals (~7.2 billion pounds over 2014–2021) is 25 times larger than the total calculable mass of SDWA chemicals over the same time (though sand and even water occasionally get marked as proprietary).[8] See supplementary materials for individual chemicals' percentages of total disclosures.

3.3. Analyzing SDWA chemical use by mass

A more comprehensive understanding of SDWA-regulated chemical use in fracking includes the mass used per disclosure. For instance, benzene is disclosed only 111 times in FracFocus (0.094% of all disclosures), yet these disclosures amount to a total mass of 7,500,000 lbs. Fig. 3 shows the mass of all SDWA-regulated chemicals per year, separated into three categories to better visualize trends. Importantly, these masses are likely undercounts because many records do not include the necessary information to calculate total mass used.

3.3.1. Large-mass chemicals

Ethylene glycol and benzene are used in the largest masses (250,000,000 lbs and 7,500,000 lbs over 2014–2021, respectively). The total mass used here mirrors the pattern of total disclosures in Fig. 2a, emphasizing ethylene glycol's large role. Despite ethylene glycol's overall decline, the smallest total mass recorded (in 2021) still amounted to about 8,300,000 lbs. Benzene's use spiked in 2019 at a total amount of 6,650,000 lbs.

3.3.2. Intermediate-mass chemicals

Within the intermediate-mass chemicals, naphthalene is used in particularly high masses. Yearly naphthalene use peaked in 2017 and 2018, with a mass of around 2,200,000 lbs per year. Its use has since declined to <200,000 lbs in 2021. Acrylamide is also used in large amounts (4,600,000 lbs used from 2014 to 2021). Its use peaked in 2018 and declined through 2021. Naphthalene and acrylamide are also the second and third-highest chemicals by disclosure.

Xylene shows a rate of considerable decline from a peak of 1,710,000 lbs in 2014 to 10,800 lbs in 2021. 1,2,4-trimethylbenzene was used relatively consistently until it peaked in 2017 with a mass of about 560,000 lbs. Its use subsequently decreased, with minimal use in 2021.

3.3.3. Small-mass chemicals

Chemicals used in smaller masses show less definitive temporal trends than those used in larger masses, though they show an overall (although unsteady) decline between 2014 and 2021. The smallest-mass chemicals (styrene, dichloromethane, di (2 ethylhexyl) phthalate, nickel, cumene, arsenic, epichlorohydrin, n-hexane, methyl chloride, and boron) are aggregated in orange in order to visualize their collective use; individually, their signal is muted by the scale of phenol use. Antimony, boron, styrene, and chlorite are the only chemicals that were used in only one year between 2014 and 2021: in 2015, 2014, 2021, and 2020, respectively.

The use of chlorite spikes in 2020 with a total mass of 21,000 lbs, while other chemicals' masses (except for phenol) and total disclosures decreased in 2020. Phenol use follows the total number of disclosures from 2014 to 2017, but while the overall disclosures increase again following 2018, phenol continues to decrease until a sudden jump in 2020. Finally, the use of 1,4-dioxane steadily decreased from ~8,000 lbs

[8] In Open-FF, many records are marked as proprietary in the "CASNumber" field but include ingredient names that imply water or sand, for example: "carrier/base fluid - water" or "silica substrate". Furthermore, the very large proprietary records have masses in the range of the two typically largest ingredients, water and sand.

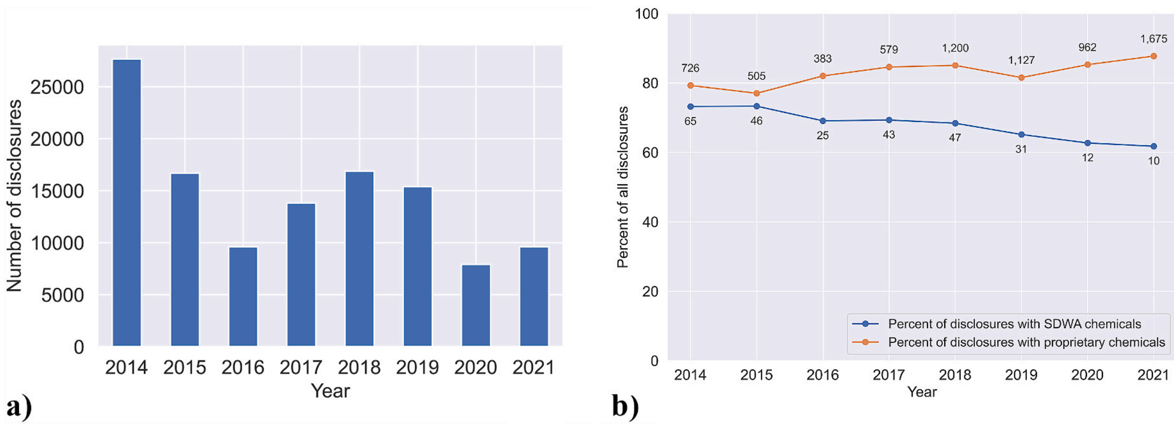

Fig. 2. a: Total disclosures within FracFocus per year, from 2014 to 2021. The total number of disclosures in our filtered data set is 117,515. Fig. 2b: Percentage of total disclosures including at least one SDWA chemical (blue: bottom line) or proprietary chemical (orange: top line) within FracFocus per year, from 2014 to 2021. The numbers above and below each dot represent the total mass of SDWA chemicals and proprietary chemicals for each year, in millions of pounds. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

in 2014 but increased again in 2019. 1,4 dioxane has since increased overall, following the total disclosure trends to FracFocus for the last three years (2019–2021) shown in Fig. 2a.

3.3.4. Understanding mass use with CERCLA reportable quantities

Returning to Table 1, many fracking disclosures report masses that exceed the RQ for hazardous substances under CERCLA.[9] Though fracking events are not subject to CERCLA's reporting requirements, RQs nonetheless provide a sense of individual chemicals' relative risks to human health, as established by the federal government and communicated in terms of mass thresholds. Therefore, they provide useful context for understanding the significance of chemicals' aggregate mass use. Fig. 4 shows the total number and percentage of disclosures for each chemical that surpass its RQ. In total, 19,700 of all disclosures exceed their RQ, and about 1126 disclosures report more than one chemical over the RQ limit. See Supplementary Materials for each SDWA-regulated chemical plotted against its RQ per year.

11,631 total disclosures of ethylene glycol exceed its RQ of 5000 lbs. Naphthalene has the second-highest number of disclosures (6,267) that surpass its RQ of 100 lbs. Acrylamide (RQ: 5000 lbs) exceeds that limit 167 times. Benzene (RQ: 10 lbs), toluene (RQ: 1000 lbs), ethylbenzene (RQ: 100 lbs), and xylene (RQ: 100 lbs) have 101, 2, 121, and 857 disclosures that exceed their RQs, respectively. However, the total number of disclosures that exceed an RQ is different from the percentage that exceed the RQ. For benzene, 91% of disclosures are above its RQ, while arsenic uses exceed its RQ in 63% of cases. 59% of 1,3-dichloropropene disclosures exceed its RQ. Six SDWA chemicals do not exceed their reporting limits (chloromethane, epichlorohydrin, cumene, dichloromethane, n-hexane, and styrene) and three only exceed their reporting limit by one or two disclosures (toluene, nickel, and di (2-ethylhexyl) phthalate).

3.4. SDWA use by operator

Fig. 5 shows the top 25 operators ranked by the number of their disclosures. More than 60% of these operators' disclosures (except EOG Resources) involve a SWDA-regulated chemical. Chesapeake Operating has a total of 2,967 disclosures with 86% using SDWA chemicals. Other top operators with SDWA-chemical disclosures include Anadarko Petroleum Corporation (2,629 disclosures) Pioneer Natural Resources (2,579 disclosures), and XTO Energy/ExxonMobil (2,500 disclosures).

Total number of disclosures does not necessarily track with the percentage of those disclosures reporting SDWA chemicals, however. For instance, although PDC only has 1,037 disclosures in total, 98% of their disclosures utilize SDWA chemicals. Similarly, 97% of Whiting Petroleum, 92% of Antero Resources Corporation, and 91% of EP Energy's disclosures use SDWA chemicals. Many of these companies are related to one another: Aera Energy, for instance, has been jointly owned by Shell and ExxonMobil since 2017 (Aera Energy, 2022) and Devon and WPX merged in September 2020 (Devon Energy and WPX Energy, 2021).

3.5. Suppliers providing SDWA chemicals in fracking

Fig. 6a shows the top direct suppliers providing SDWA chemicals for fracking jobs. Halliburton is the most commonly named supplier. However, "supplier" is not a required field in FracFocus' disclosure form, and many suppliers are listed for one fracking job. The largest number of disclosures (33,862) reporting SDWA chemicals have suppliers labeled "company name not reported." Additionally, the eighth-ranked supplier (2,080 disclosures) is "non-company name reported." Consequently, the disclosures without a listed supplier are 6.5 times greater than those supplied by Halliburton. The next top named suppliers include Chemplex, Schlumberger, and Liberty Oilfield Services.

Again, total numbers of disclosures show a different pattern than the percentage of disclosures containing SDWA chemicals. Although disclosures using SDWA chemicals only make up 19% and 25% of Halliburton and Chemplex's disclosures respectively, they comprise 55% of Schlumberger's and 75% of Liberty Oilfield Services's disclosures. The only suppliers that use SDWA chemicals in more than 80% of their total disclosures are ASK and U.S. Well Services.

In the absence of direct supplier information, we also analyzed the suppliers most associated with a given fracking job. As shown by Fig. 6b, Halliburton is the supplier most associated with disclosures using SDWA-regulated chemicals, with more than 18,750 disclosures. This is 68% of their total FracFocus disclosures. Schlumberger, the next most

[9] Defined in Tabl 302.4 of the Federal Register (40 CRF 302.4) and originally listed in CERCLA Section 102(a). This list has since been updated multiple times, including by the Emergency Planning and Community Right to Know Act, otherwise known as Title III of the 1986 Superfund Amendments and Reauthorization Act (SARA), which was a major amendment to CERCLA. Five chemicals (1,2,4-Trimethylbenzene, 1,3,5-Trimethylbenzene, boron, chlorine dioxide, and chlorite) are not on this list. Though fracking events are not regulated by CERCLA, if there were an accidental spill of a chemical in a mass greater than its RQ, then it would need to be reported under CERCLA's jurisdiction.

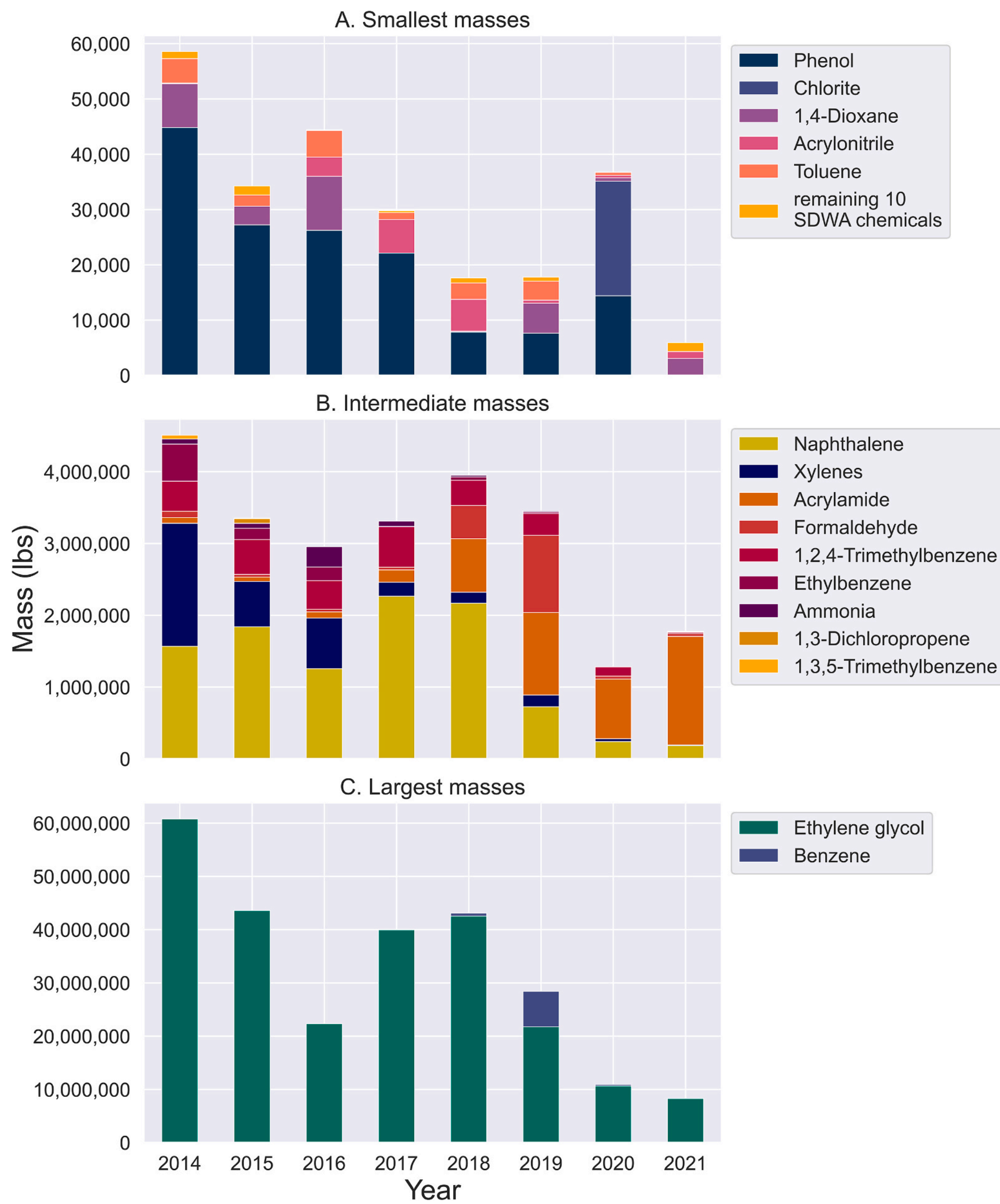

Fig. 3. Calculated mass used per year for 28 SDWA chemicals from 2014 to 2021. Fig. 3a shows the chemicals used in the smallest masses; Fig. 3b shows the chemicals used in intermediate masses; Fig. 3c shows the chemicals used in the largest masses.

associated supplier, has only 7157 disclosures that utilize SDWA-regulated chemicals, but this is 96% of their disclosures. Similar to operators, supplier companies often merge as well: Nabors and C&J Well merged in 2015 (C&J Energy Services and Nabors, 2022).

4. Discussion

Overall, SDWA-regulated chemicals are widespread across FracFocus. Of the 306 chemicals listed under the NPDWR and DWSHA, 28 (10%) were disclosed in fracking events from 2014 to 2021. More than 60% of each operator's disclosures include at least one SDWA chemical, and SDWA chemicals were reported in over 60% of all disclosures between 2014 and 2021 (range of 62–73%). Each of these chemicals is associated with serious health effects.

19,700 disclosures (about 17% of total FracFocus disclosures) report masses that exceed CERCLA RQs. All 28 SDWA-regulated chemicals except six exceeded their RQ at least once, though the percentage of exceeding disclosures varied: 91% of benzene disclosures exceeded its RQ, while 41% of naphthalene; 22% of ethylene glycol; 6% of formaldehyde; and 1% of 1,4-dioxane disclosures exceeded their RQs.

Importantly, we report masses per individual well, rather than per well pad, upon which multiple wells can be located. There are likely many more well pads where aggregate releases exceed RQs. The prevalence of disclosures in which chemicals' use exceeds their RQs raises a concern about the oil industry's exemption from community right-to-know laws such as EPCRA (Hatzenbuhler and Centner, 2012).

4.1. *Most frequently disclosed chemicals*

Ethylene glycol, naphthalene, acrylamide, and formaldehyde are most often disclosed. This consistency suggests they play a more integral role in the fracking process compared to the other SDWA-regulated chemicals. Their proportions of use shift over time and may oppose or follow the fracking market's trends (Fig. 3). These changes could reflect differing production techniques or physical environments, or geologic conditions.

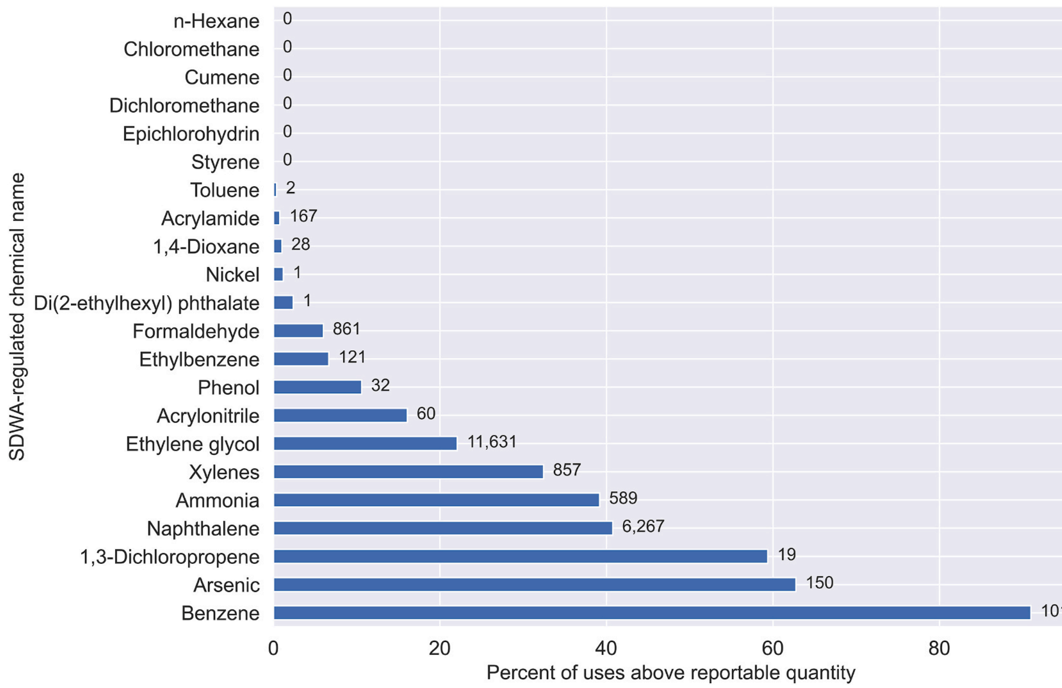

Fig. 4. Total number and percentage of all disclosures for each SDWA chemical that surpass its Reportable Quantity as defined by CERCLA.

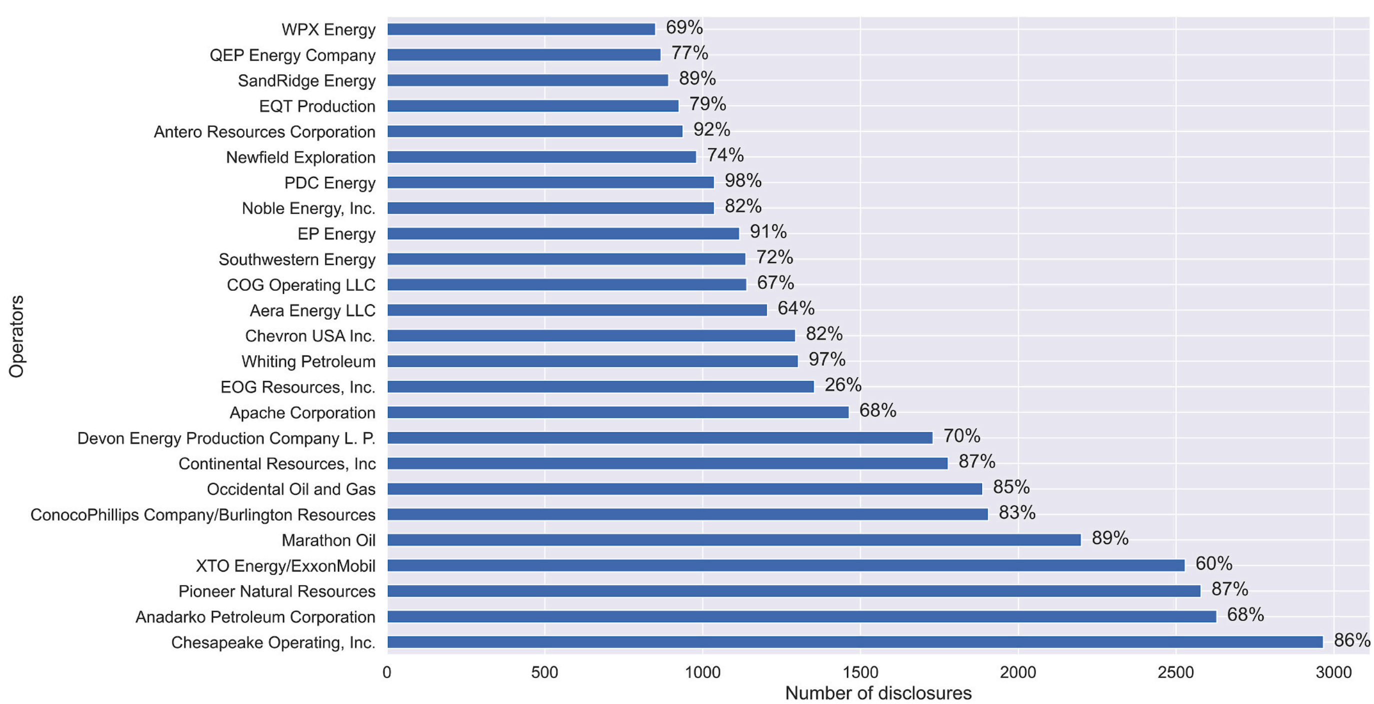

Fig. 5. Top 25 operators using SDWA-regulated chemicals, ranked in order of number of disclosures, 2014–2021. The percentage at the end of the bar represents the percentage of that company's disclosures that use at least one SDWA chemical.

Ethylene glycol is disclosed in around 45% of fracks as a crosslinker, friction reducer, gelling agent, and non-emulsifier (107-21-1: Ethanediol, 2022). For a sense of scale, the total ethylene glycol reported in fracking from 2014 to 2021 (250 million pounds) amounts to about 7% of US yearly production capacity (1.63 million metric tons) (Fernández, 2022a, 2022b). The decrease in ethylene glycol use, percentage-wise, likely mirrors the general decrease in chemical percentages (within a typical frack) across the industry as the median size of fracks has grown (Open-FF Scope and Aggregate Stats, 2022). Interestingly, ethylene glycol is derived from ethylene, which is frequently derived from natural gas via the process of "cracking" to make plastics (Wylie, 2018). Further analysis should investigate fracking's role as both the feedstock and energy for ethylene cracking, and a significant new market for ethylene-derived chemicals.

Second to ethylene glycol, acrylamide was disclosed in 19% of all fracks and primarily reported as a friction reducing agent (79-06-1: 2-Propenamide/Acrylamide, 2022). Next, naphthalene, a pesticide in mothballs, is also a fossil fuel product derived from crude oil or tar

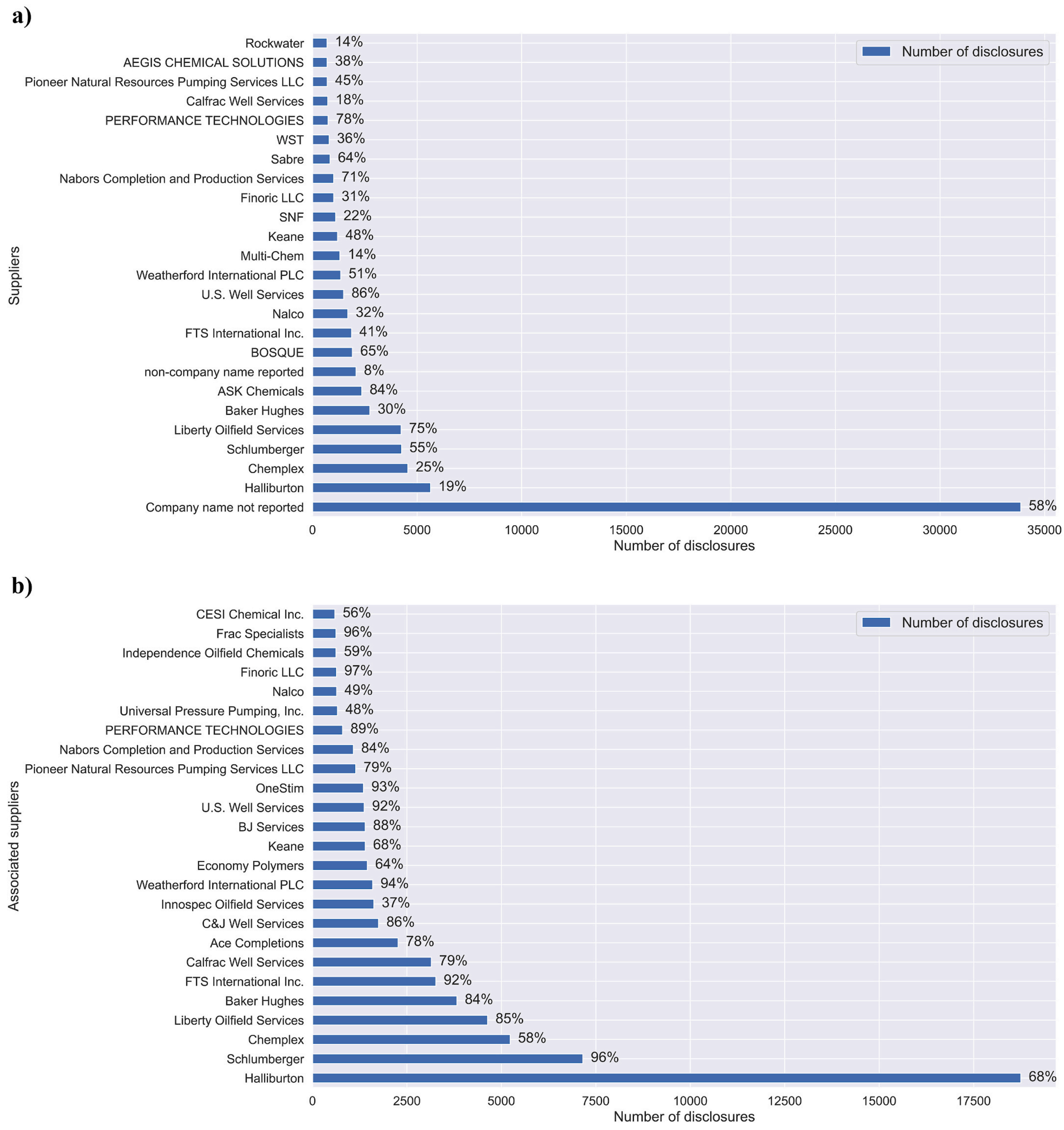

Fig. 6. a: Top suppliers of 28 SDWA-rcgulated chemicals from 2014 to 2021. This figure shows the top 25 suppliers who provide these chemicals, ranked in order of the total number of disclosures that include SDWA-rcgulated chemicals. The percentage at the end of the bar represents the percentage of that company's total disclosures that use at least one SDWA chemical. Fig. 6b: Top associated suppliers of the 28 SDWA-rcgulated chemicals from 2014 to 2021. This figure highlights the 25 suppliers who are most frequently associated with a fracking event that used SDWA-rcgulated chemicals, but are not necessarily identified as the direct supplier. The percentage at the end of the bar represents the percentage of the disclosures each supplier is associated with that utilize at least one SDWA-rcgulated chemical.

(Gervais et al., 2010). In fracking, naphthalene is used primarily as a surfactant, reducing the surface tension between oil and water to extract oil from rock (91-20-3: Naphthalene, 2022). Last, formaldehyde, a colorless, strong-smelling gas, was used primarily as a biocide in 12% of total disclosures (50-00-0: Formaldehyde, 2022). Elevated levels of formaldehyde have been found around fracking sites due to trucking traffic and methane's conversion to formaldehyde (Carpenter, 2016).

4.2. *Less frequently disclosed chemicals*

Other chemicals are used in low masses or disclosed less frequently. However, they are not necessarily of less concern: many chemicals can be hazardous even at low concentrations, as the RfDs and MCLs in Table 1 demonstrate. For example, 1,4-dioxane is disclosed 2,747 times at yearly masses around 3,800 lbs, but its RfD is only 0.03 mg/kg/day. It is also present in groundwater sites throughout the United States: as of 2016, it had been identified at more than 31 sites on the EPA's National Priorities List (NPL) and in more than 20% of the U.S. public drinking water supply (Godri Pollitt et al., 2019). Why its use increased in 2019 after having declined since 2014 is unclear (Fig. 3).

Benzene is derived from crude oil and widely used to produce pesticides, plastics, resins, pharmaceuticals, and dyes (Centers for Disease Control and Prevention, 2019). While its total *number* of disclosures (111) is small, the total mass reported is 7.5 million lbs due to a large spike in 2019, primarily in Texas, in which 6,650,000 lbs of benzene were used in one year. This spike could be due to the characterization and then reuse of produced water to reduce the volume of fresh water used: many of the large benzene records are assigned the trade name "produced water" in the actual disclosure records (71-43-2: Benzene, 2022; Cooper et al., 2022). The benzene concentrations reported in Open-FF (0.1%) are slightly higher than those reported for produced water in Texas' Permian Basin (Al-Ghouti et al., 2019). In contrast, many other "produced water" disclosures only report a single ingredient: 7732-18-5 (water) which suggests a lack of analysis for its chemical constituents. The presence of benzene within produced water is concerning because produced water is also used to spray dirt roads, water crops, and other "beneficial uses" (Chittick and Srebotnjak, 2017; Lauer et al., 2018; McDevitt et al., 2019; McLaughlin et al., 2020). One analysis of fracking produced water found measurable and, in some cases, elevated concentrations of BTEX chemicals in 95% of wells (Chittick and Srebotnjak, 2017).

High benzene levels in produced water could also derive from the use of petroleum distillates in fracking. Distillates, often used as friction reducers, are produced by distilling crude oil, yet their precise composition is rarely reported. Prior research indicates that fracking companies are increasingly using petroleum distillates, many of which contain high levels of benzene and other BTEX chemicals: up to 93,000 parts per million for naphtha solvents (Pagnotto et al., 1961) or 10,000 parts per million for a particular brand of mineral spirits (Hunting et al., 1995). In other words, the high benzene levels in 2019 could reflect reuse of produced water containing petroleum distillates with high BTEX concentrations.

Finally, 1,3-dichloropropene has an MCL of 0.0005 mg/L, which means that it is two times more potent than benzene (California Office of Environmental Health, 2022). Comparatively, the mass of 1,3-dichloropropene used is 112 times less than the mass of benzene used (67,000 lbs vs. 7,500,000 lbs of benzene), yet its regulatory threshold indicates that more than half of a teaspoon in an Olympic-sized swimming pool is unsafe. Therefore, even when chemicals are being used in smaller amounts, their mass is not necessarily indicative of their relative hazard.

4.3. Unknowns and proprietaries

Our data show the scale of proprietary chemicals used in fracking: the masses of proprietary chemicals (over 7.2 billion lbs from 2014 to 2021) far outweigh the masses of reported SDWA-regulated chemicals. The percentage of disclosures including at least one proprietary chemical has steadily increased since 2014 (Fig. 2b), which may reflect the industry's reaction to EPA's UIC Program Guidance #84 in 2014. Because diesel fuels were the only exception to the Halliburton Loophole, this Guidance clarified which chemical names were considered "diesel fuels" and therefore subject to SDWA regulation (US EPA, 2014). Now, diesel fuels could potentially still be used under proprietary chemical claims. Interestingly, as proprietary chemical reports increased, disclosures of SDWA-regulated chemicals decreased. However, there is no way to know whether and how much SDWA-regulated chemicals are included in proprietary claims.

Our findings are generally consistent with others: a 2014 report by the US Department of Energy (U.S. Department of Energy, 2014) noted that approximately 84% of disclosures between 2011 and June 1, 2013 withheld at least one chemical ingredient as proprietary or trade secret. Trickey et al. (2020) identified proprietary withholding in 87% of disclosures submitted from 2011–18, even after FracFocus' implementation of the systems approach, which ostensibly aimed to reduce proprietary claims. Attention to proprietary claims is important: for instance, our findings are generally consistent with Hill et al.'s report of 1,244 unique fracking chemicals disclosed to FracFocus between 2014 and 2020 (Hill et al., 2022). However, while they infer from a 32.3% decrease in annual unique chemical counts that data quality and transparency has increased, they do not account for the increase in proprietary chemical claims over the same time period.

Reducing proprietary claims in fracking disclosures is important as the precise composition of two thousand pounds of "X proprietary mixture" could contain anything (including SDWA-regulated chemicals). Future research on these proprietary claims could help contextualize the opposing trends between SDWA and proprietary chemicals shown in Fig. 2b, or the 2019 benzene spike shown in Fig. 3. Similarly, studies that link produced water with injected fluids could close some of these information gaps (e.g., Getzinger et al., 2015; Luek and Gonsior, 2017; Rosenblum et al., 2017). Finally, the fact that some fracking events in this study utilized zero proprietary chemicals suggests that further research comparing fracking events that use zero proprietary chemicals to fracks where the majority of chemicals are reported as proprietary is warranted, to understand why there is such a large range (0–87%) in proprietary chemical usage.

4.4. SDWA-regulated chemical use across operator and supplier

Recent studies demonstrate that the oil and gas industry is broadly aware that its products and practices are detrimental to climate change, and companies have actively sought to discredit climate science in order to protect their assets (Bedford, 2010). Accordingly, some climate change research has moved from a nation-level to a corporate-level analysis to emphasize corporate accountability - though not to the exclusion of public policy change (Heede, 2014; Grasso, 2019; Licker et al., 2019; Varvastian and Kalunga, 2020). We employ an analogous method here, analyzing disclosures at the company level to emphasize corporate use and accountability.

The top operators using SDWA-regulated chemicals included Chesapeake Operating, Inc., Anadarko Petroleum Corporation, Pioneer Natural Resources, and XTO Energy/ExxonMobil. The top named supplier was Halliburton - yet Halliburton's disclosures were surpassed by the category "company name not reported" by around 28,224 disclosures. In aggregate, Halliburton has clearly benefited from this regulatory exemption. Moreover, the systems approach (discussed in "Materials and Methods" above) structurally disconnects chemicals and their suppliers, producing a further range of unknowns by disconnecting fracking chemicals from supply chains and limiting corporate legal liability.

To further illuminate supply chains, therefore, we examine "Associated Suppliers" to show which companies are most often named in a given disclosure (Fig. 6b). Halliburton's association with SDWA-regulated chemicals is even clearer in this figure, with the company appearing in disclosures of SDWA-regulated chemicals almost ten times more than the next most-common company.

Ultimately, the Halliburton loophole and other oil and gas exemptions from federal environmental legislation limits research on fracking's public and environmental health impacts and limits corporations' legal liability for those impacts.

5. Limitations

Because FracFocus.org relies on industry self-reports (though in some states reporting is mandated), analysis is ultimately limited to what and how operators disclose their data. While a similar aggregate-chemical study (Hill et al., 2022) concluded that FracFocus has improved data transparency over the last ten years, we come to the opposite conclusion, finding the same issues of "opaque transparency" that other researchers have previously identified (Kinchy and Schaffer, 2018; Avidan et al., 2019; U.S. Department of Energy, 2014).

We did not provide a state-by-state analysis, even though much environmental policy is enacted at the state level, because disparate reporting requirements precluded clear comparisons across states. Further, the breadth of proprietary claims limit a full understanding of state-level trends in SDWA-regulated chemical use. However, state-level analyses (rather than state vs. state comparisons) remain useful for policy development at more local levels. Future analysis should analyze the trends of SDWA-regulated chemical use in relationship to US Drinking Water Sources (USDWs) or in combination with environmental justice tools such as the EPA's EnviroScreen.

Open-FF's ability to calculate mass requires several pieces of data in individual disclosures that are often missing, such as total volume of the fracking event and percent of the chemical used. Therefore, our mass analysis is likely an undercount. Finally, while FracFocus.org began in 2011, its data reporting tools were inconsistent until 2014. Therefore, our analysis focuses only on 2014–2021.

6. Conclusion and recommendations

Given the evidence that hydraulic fracturing impacts drinking water and human and environmental health, we suggest three broad recommendations below, which broadly align with other reports, including the Department of Energy's 2014 Task Force on FracFocus (U.S. Department of Energy, 2014).

Recommendation 1. Mandated Federal Disclosure Database

Insufficient regulatory oversight, including the absence of a federally mandated disclosure mechanism, enables fracking companies to exploit trade secret provisions and "evade the rules at will" (McFeeley, 2014). While some states are mandated to utilize FracFocus to disclose their fracking events, many states are not (see footnote 3). This means that FracFocus does not fully depict fracking chemical use across the US. A federally mandated disclosure base through EPA, DOE, or the National Institute of Environmental Health Sciences (NIEHS) is necessary for thorough and meaningful research on the chemical impacts of fracking. At minimum, public health research requires full disclosure of all chemicals used in fracking, including proprietary chemicals, and all supplier names.

At minimum, FracFocus should be subject to federal records guidelines to ensure that chemical records are systematically archived and accessible whenever they are needed in the future, and state agencies should mandate regular downloading of FracFocus data to ensure that FracFocus' millions of chemical records are never corrupted or deleted. This would enable investigating and flagging disclosures altered by companies after their initial submission; currently, operators are able to revise and resubmit entries without alerting the public. In addition, we recommend improved quality control measures within FracFocus to ensure that accurate values are being stored within the database. We recommend that future iterations of the FracFocus dataset be fashioned in accordance with FAIR Principles for Open Data, a framework that would ensure that HF chemical disclosures are effectively Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016).

Recommendation 2. Toxicological and Environmental Forensics Research.

Recommendation 1 would enable another important step: conducting exposure pathway and environmental forensics studies for fracking chemicals. Using full toxicological and exposure-science methodologies, future studies can explore these chemicals' fate and transport within the environment, possible exposure pathways, and associated impacts. This research would further quantify the impacts of the Halliburton Loophole and other regulatory exemptions not only in terms of chemical mass but in terms of human and environmental health.

Further research should also investigate combinations of fracking chemicals; while here we discuss them individually, they are always used in combinations that can shift or exacerbate their hazardous effects. Distillates also remain a major knowledge gap: hundreds of different distillates are listed in the FracFocus database, but their specific ingredients and chemical makeup remain opaque. Future research should also investigate endocrine-disrupting chemicals (EDCs) in fracking fluid, using ToxCast or other endpoint databases. Finally, further research should investigate the composition of produced water - especially in the face of increasing interest in its potential beneficial uses, as discussed above.

Recommendation 3. Repeal Exemptions for Fracking Activity and Reduce Proprietary Claims

Based on this analysis and existing evidence of water contamination documented in the scientific literature, we recommend that the Halliburton Loophole be repealed and fracking be regulated under SDWA. We also follow Avidan et al.'s (2019) recommendation that the oil and gas industry's reporting exemption from the Toxics Release Inventory (TRI) be revoked. Incomplete information about chemical use and the companies responsible, as required by EPCRA, constrains impacted communities' targeted water monitoring or pursuit of accountability for damages. Other exemptions, under the Clean Water Act and CERCLA, should also be re-examined. Finally, the high number of proprietary claims limits possible research. Like the DOE's FracFocus Task Force, we suggest strict standards and challenge mechanisms for any proprietary claims (U.S. Department of Energy, 2014).

Ultimately, because regulatory exemptions have historically created these gaps in public health knowledge, it is vital to close these gaps through research and monitoring on fracking activity and its potential impacts on human and environmental health.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vivian Underhill reports financial support was provided by National Institute of Environmental Health Sciences T32 Postdoctoral Grant.

Data availability

Data are available at: https://codeocean.com/capsule/9423121/tree/v14. The Jupyter notebooks used in this analysis are available at: https://github.com/gwallison/SDWA_EP_publication.

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Appendix A. Supplementary data

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References

06-1:2-Propenamide/Acrylamide., 2022. Open-FF Chemical Reports [cited 2022 Oct 19]. Available from: https://qbobioyuz1dh57rst8exeg.on.drv.tw/open_FF_catalog/79-06-1/analysis_79-06-1.html.

50-00-0: Formaldehyde, 2022. Open-FF Chemical Reports [cited 2022 Oct 19]. Available from: https://qbobioyuz1dh57rst8exeg.on.drv.tw/open_FF_catalog/50-00-0/analysis_50-00-0.html.

71-43-2: Benzene. Open-FF Chemical Reports, 2022 [cited 2022 Oct 19]. Available from: https://qbobioyuz1dh57rst8exeg.on.drv.tw/open_FF_catalog/71-43-2/analysis_71-43-2.html#raw.

91-20-3: Naphthalene. Open-FF Chemical Reports, 2022. Available from: https://qbobioyuz1dh57rst8exeg.on.drv.tw/open_FF_catalog/91-20-3/analysis_91-20-3.html#patterns.

107-21-1: Ethanediol., 2022. https://qbobioyuz1dh57rst8exeg.on.drv.tw/open_FF_catalog/107-21-1/analysis_107-21-1.html.

Aera Energy is jointly owned by affiliates of Shell and ExxonMobil [Internet]. Aera Energy. [cited 2022 Apr 29]. Available from: https://www.aeraenergy.com/facts/aera-energy-is-jointly-owned-by-affiliates-of-shell-and-exxonmobil/.

Agency for Toxic Substances and DIsease Registry, 2007. Toxicological Profile for Benzene [cited 2022 Oct 19]. Available from: https://www.epa.gov/foia/toxicological-profile-benzene.

Agency for Toxic Substances and DIsease Registry. Medical management guidelines for formaldehyde. Medical Management Guidelines (MMG) for Acute Chemical Exposure. [cited 2022 Oct 19]. Available from: https://www.atsdr.cdc.gov/MHMI/mmg111.pdf.

Al-Ghouti, M.A., Al-Kaabi, M.A., Ashfaq, M.Y., Da'na, D.A., 2019. Produced water characteristics, treatment and reuse: a review. Apr 1 J. Water Proc. Eng. 28, 222–239.

Allison, G.. Open-FF: transforming the FracFocus disclosure data into a useable resource [Source Code]. 2022 Apr 7 [cited 2022 Apr 13]; Available from: https://codeocean.com/capsule/9423121/tree/v14.

Avidan, M., Etzion, D., Gehman, J., 2019. Opaque transparency: how material affordances shape intermediary work. Regul Gov 13 (2), 197–219.

Bedford, D., 2010. Agnotology as a teaching tool: learning climate science by studying misinformation. Jul 28 J. Geogr. 109 (4), 159–65.

Burton, G.A., Basu, N., Ellis, B.R., Kapo, K.E., Entrekin, S., Nadelhoffer, K., 2014. Hydraulic "fracking": are surface water impacts an ecological concern? Aug Environ. Toxicol. Chem. 33 (8), 1679–1689.

C&J Energy Services and Nabors Industries complete combination transaction. [cited 2022 Apr 29]. Available from: https://www.prnewswire.com/news-releases/cj-energy-services-and-nabors-industries-complete-combination-transaction-300055229.html.

California Office of environmental health hazard assessment. 1,3-Dichloropropene. California OEHHA. 2022 [cited 2022 Oct 19]. Available from: https://oehha.ca.gov/chemicals/13-dichloropropene.

Carpenter, D.O., 2016. Hydraulic fracturing for natural gas: impact on health and environment. Mar;31 Rev. Environ. Health (1), 47–51.

Casey, J.A., Savitz, D.A., Rasmussen, S.G., Ogburn, E.L., Pollak, J., Mercer, D.G., et al., 2016. Unconventional natural gas development and birth outcomes in Pennsylvania, USA. Mar Epidemiol. Camb. Mass. 27 (2), 163–172.

Centers for Disease Control and Prevention. Facts About Benzene [Internet]. 2019 [cited 2022 Apr 26]. Available from: https://emergency.cdc.gov/agent/benzene/basics/facts.asp.

Chittick, E.A., Srebotnjak, T., 2017. An analysis of chemicals and other constituents found in produced water from hydraulically fractured wells in California and the challenges for wastewater management. J. Environ. Manag. 204–502. Dec 15.

Cooper, C.M., McCall, J., Stokes, S.C., McKay, C., Bentley, M.J., Rosenblum, J.S., et al., 2022. Oil and gas produced water reuse: opportunities, treatment needs, and challenges. Mar 11 ACS EST Eng. 2 (3), 347–366.

Cupas, A.C., 2008. The Not-so-safe Drinking Water Act: why we must regulate hydraulic fracturing at the federal level, 2009 William Mary Environ. Law Pol. Rev. 33 (2), 605–632.

Czolowski, E.D., Santoro, R.L., Srebotnjak, T., Shonkoff, S.B.C., 2017. Toward consistent methodology to quantify populations in proximity to oil and gas development: a national spatial analysis and review. Environ. Health Perspect. 125 (8), 086004.

Devon Energy and WPX Energy complete merger of equals transaction [Internet]. GlobeNewswire News Room. 2021 [cited 2022 Apr 29]. Available from: https://www.globenewswire.com/news-release/2021/01/07/2154994/0/en/Devon-Energy-and-WPX-Energy-Complete-Merger-of-Equals-Transaction.html.

Drollette, B.D., Hoelzer, K., Warner, N.R., Darrah, T.H., Karatum, O., O'Connor, M.P., et al., 2015. Elevated levels of diesel range organic compounds in groundwater near Marcellus gas operations are derived from surface activities. Oct 27 Proc. Natl. Acad. Sci. USA 112 (43), 13184–13189.

Elliott, E.G., Trinh, P., Ma, X., Leaderer, B.P., Ward, M.H., Deziel, N.C., 2017. Unconventional oil and gas development and risk of childhood leukemia: assessing the evidence. Jan 15 Sci. Total Environ. 576, 138–147.

Fernández, L.. Production capacity of ethylene glycol worldwide from 2014 to 2025 [Internet]. Statista. 2022 [cited 2022 Jun 16]. Available from: https://www.statista.com/statistics/1067418/global-ethylene-glycol-production-capacity/.

Fernández, L.. Ethylene glycol production in the United States from 2009 to 2019 [Internet]. Statista. 2022 [cited 2022 Jun 16]. Available from: https://www.statista.com/statistics/974784/us-ethylene-glycol-production-volume/.

Fontenot, B.E., Hunt, L.R., Hildenbrand, Z.L., Carlton Jr., D.D., Oka, H., Walton, J.L., et al., 2013. An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett shale formation. Sep 3 Environ. Sci. Technol. 47 (17), 10032–10040.

FracFocus Scope and Aggregate Stats. Open-FF, 2022 [cited 2022 Oct 19]. Available from: https://qbobioyuz1dh57rst8exeg.on.drv.tw/open_FF_catalog/Open-FF_Scope_and_Aggregate_Stats.html#water_use.

Gervais, J., Luukinen, B., Buhl, K., Stone, D., 2010. Naphthalene General Fact Sheet [Internet]. National Pesticide Information Center, Oregon State University Extension Services [cited 2022 Apr 26]. Available from: http://npic.orst.edu/factsheets/naphgen.html.

Getzinger, G.J., O'Connor, M.P., Hoelzer, K., Drollette, B.D., Karatum, O., Deshusses, M.A., et al., 2015. Natural gas residual fluids: sources, endpoints, and organic chemical composition after centralized waste treatment in Pennsylvania. Jul 21 Environ. Sci. Technol. 49 (14), 8347–8355.

Gilmore, K.R., Hupp, R.L., Glathar, J., 2014. Transport of hydraulic fracturing water and wastes in the Susquehanna River Basin, Pennsylvania. May 1 J. Environ. Env. 140 (5), B4013002.

Godri Pollitt, K.J., Kim, J.H., Peccia, J., Elimelech, M., Zhang, Y., Charkoftaki, G., et al., 2019. 1,4-Dioxane as an emerging water contaminant: state of the science and evaluation of research needs. Nov 10 Sci. Total Environ. 690, 853–866.

Grasso, M., 2019. Oily politics: a critical assessment of the oil and gas industry's contribution to climate change. Apr 1 Energy Res. Social Sci. 50, 106–15.

Hall, K.B., 2011. Regulations of hydraulic fracturing under the safe drinking water Act, 2012 Buffalo Environ. Law J. 19 (1), 1–42.

Hatzenbuhler, H., Centner, T.J., 2012. Regulation of water pollution from hydraulic fracturing in horizontally-drilled wells in the Marcellus shale region. Dec USA. Water 4 (4), 983–994.

Heede, R., 2014. Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010. Jan 1 Clim. Change 122 (1), 229–41.

Hill, C.B., Yadav, O.P., Khan, E., 2022. Examining hydraulic fracturing chemicals: a temporal and comparative analysis. Jan 1 Water Res. 208, 117878.

Hunting, K.L., Longbottom, H., Kalavar, S.S., Stern, F., Schwartz, E., Welch, L.S., 1995. Haematopoietic cancer mortality among vehicle mechanics. Oct Occup. Environ. Med. 52 (10), 673–678.

Ingraffea, A.R., Wells, M.T., Santoro, R.L., Shonkoff, S.B.C., 2014. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. Jul 29 Proc. Natl. Acad. Sci. U. S. A. 111 (30), 10955–10960.

Jackson, R.B., Vengosh, A., Darrah, T.H., Warner, N.R., Down, A., Poreda, R.J., et al., 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Jul 9 Proc. Natl. Acad. Sci. USA 110 (28), 11250–11255.

Jemielita, T., Gerton, G.L., Neidell, M., Chillrud, S., Yan, B., Stute, M., et al., 2015. Unconventional gas and oil drilling is associated with increased hospital utilization rates. Jul 15 PLoS One 10 (7), e0131093.

Kahrilas, G.A., Blotevogel, J., Stewart, P.S., Borch, T., 2015. Biocides in hydraulic fracturing fluids: a critical review of their usage, mobility, degradation, and toxicity. Jan 6 Environ. Sci. Technol. 49 (1), 16–32.

Kassotis, C.D., Tillitt, D.E., Davis, J.W., Hormann, A.M., Nagel, S.C., 2014. Estrogen and androgen receptor activities of hydraulic fracturing chemicals and surface and ground water in a drilling-dense region. Mar Endocrinology 155 (3), 897–907.

Kinchy, A., Schaffer, G., 2018. Disclosure conflicts: crude oil trains, fracking chemicals, and the politics of transparency. Nov 1 Sci. Technol. Hum. Val. 43 (6), 1011–1038.

Konschnik, K., Holden, M., Shasteen, A., 2013. Legal Fractures in Chemical Disclosures Laws: Why the Voluntary Chemical Disclosure Registry FracFocus Fails as a Regulatory Compliance Tool [Internet]. Apr. Harvard Law School Environmental Law Program. Available from: https://legacy-assets.eenews.net/open_files/assets/2013/04/23/document_ew_01.pdf.

Lauer, N.E., Warner, N.R., Vengosh, A., 2018. Sources of radium accumulation in stream sediments near disposal sites in Pennsylvania: implications for disposal of conventional oil and gas wastewater. Feb 6 Environ. Sci. Technol. 52 (3), 955–62.

Licker, R., Ekwurzel, B., Doney, S.C., Cooley, S.R., Lima, I.D., Heede, R., et al., 2019. Attributing ocean acidification to major carbon producers. Dec Environ. Res. Lett. 14 (12), 124060.

Llewellyn, G.T., Dorman, F., Westland, J.L., Yoxtheimer, D., Grieve, P., Sowers, T., et al., 2015. Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. May 19 Proc. Natl. Acad. Sci. U. S. A. 112 (20), 6325–6330.

Luek, J.L., Gonsior, M., 2017. Organic compounds in hydraulic fracturing fluids and wastewaters: a review. Oct 15 Water Res. 48, 123–536.

Mauter, M.S., Alvarez, P.J.J., Burton, A., Cafaro, D.C., Chen, W., Gregory, K.B., et al., 2014. Regional variation in water-related impacts of shale gas development and implications for emerging international plays. Environ. Sci. Technol. 48 (15), 8298–8306.
McAlexander, T.P., Bandeen-Roche, K., Buckley, J.P., Pollak, J., Michos, E.D., McEvoy, J. W., et al., 2020. Unconventional natural gas development and hospitalization for heart failure in Pennsylvania. Dec 15 J. Am. Coll. Cardiol. 76 (24), 2862–2874.
McDevitt, B., McLaughlin, M., Cravotta, C.A., Ajemigbitse, M.A., Sice, K.J.V., Blotevogel, J., et al., 2019. Emerging investigator series: radium accumulation in carbonate river sediments at oil and gas produced water discharges: implications for beneficial use as disposal management. Feb 21 Environ. Sci. Process Impacts 21 (2), 324–38.
McEachran, A.D., Sobus, J.R., Williams, A.J., 2017. Identifying known unknowns using the US EPA's CompTox Chemistry Dashboard. Mar 1 Anal. Bioanal. Chem. 409 (7), 1729–1735.
McFeeley, M., 2014. Falling through the cracks: public information and the patchwork of hydraulic fracturing disclosure laws. Vt. Law Rev. 38 (4).
McKenzie, L.M., Witter, R.Z., Newman, L.S., Adgate, J.L., 2012. Human health risk assessment of air emissions from development of unconventional natural gas resources. May 1 Sci. Total Environ. 424, 79–87.
McKenzie, L.M., Guo, R., Witter, R.Z., Savitz, D.A., Newman, L.S., Adgate, J.L., 2014. Birth outcomes and maternal residential proximity to natural gas development in rural Colorado. Environ. Health Perspect. 122 (4), 412–417.
McLaughlin, M.C., Borch, T., McDevitt, B., Warner, N.R., Blotevogel, J., 2020. Water quality assessment downstream of oil and gas produced water discharges intended for beneficial reuse in arid regions. Apr 15 Sci. Total Environ. 713, 136607.
McMahon, P.B., Barlow, J.R.B., Engle, M.A., Belitz, K., Ging, P.B., Hunt, A.G., et al., 2017. Methane and benzene in drinking-water wells overlying the Eagle Ford, Fayetteville, and Haynesville shale hydrocarbon production areas. Jun 20 Environ. Sci. Technol. 51 (12), 6727–6734.
National Cancer Institute, 2017. Acrylamide and Cancer Risk. NIH National Cancer Institute [cited 2022 Oct 19]. Available from: https://www.cancer.gov/about-cancer/causes-prevention/risk/diet/acrylamide-fact-sheet.
National Institute of Occupational Safety and Health. Ethylene Glycol: Systemic Agent [Internet]. 2021 [cited 2022 Apr 26]. Available from: https://www.cdc.gov/niosh/ershdb/emergencyresponsecard_29750031.html.
Ogneva-Himmelberger, Y., Huang, L., 2015. Spatial distribution of unconventional gas wells and human populations in the Marcellus Shale in the United States: vulnerability analysis. Jun 1 Appl. Geogr. 60, 165–174.
Osborn, S.G., Vengosh, A., Warner, N.R., Jackson, R.B., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. May 17 Proc. Natl. Acad. Sci. USA 108 (20), 8172–8176.
Pagnotto, L.D., Elkins, H.B., Brugsch, H.G., Walkley, J.E., 1961. Industrial benzene exposure from petroleum naphtha. I. Rubber coating industry. Dec Am. Ind. Hyg. Assoc. J. 22, 417–421.
Rasmussen, S.G., Ogburn, E.L., McCormack, M., Casey, J.A., Bandeen-Roche, K., Mercer, D.G., et al., 2016. Association between unconventional natural gas development in the Marcellus Shale and asthma exacerbations. Sep 1 JAMA Intern. Med. 176 (9), 1334–1343.
Rosenblum, J., Thurman, E.M., Ferrer, I., Aiken, G., Linden, K.G., 2017. Organic chemical characterization and mass balance of a hydraulically fractured well: from fracturing fluid to produced water over 405 Days. Dec 5 Environ. Sci. Technol. 51 (23), 14006–14015.
Shaffer, R.M., 2021. Environmental health risk assessment in the federal government: a visual overview and a renewed call for coordination. Aug 17 Environ. Sci. Technol. 55 (16), 10923–10927.
Shamasunder, B., Morello-Frosch, R., 2016. Scientific contestations over "toxic trespass": health and regulatory implications of chemical biomonitoring. J. Environ. Stud. Sci. 6, 556–568.
Silva, G.S., Warren, J.L., Deziel, N.C., 2018. Spatial modeling to identify sociodemographic predictors of hydraulic fracturing wastewater injection wells in Ohio census block groups. Jun Environ. Health Perspect. 126 (6), 067008.
Trickey, K., Hadjimichael, N., Sanghavi, P., 2020. Public reporting of hydraulic fracturing chemicals in the USA, 2011–18: a before and after comparison of reporting formats. May 1 Lancet Planet. Health 4 (5). e178–85.
Tustin, A.W., Hirsch, A.G., Rasmussen, S.G., Casey, J.A., Bandeen-Roche, K., Schwartz, B. S., 2017. Associations between unconventional natural gas development and nasal and sinus, migraine headache, and fatigue symptoms in Pennsylvania. Feb Environ. Health Perspect. 125 (2), 189–197.
U.S. Department of Energy, 2014. Secretary of Energy Advisory Board Task Force Report on FracFocus 2.0 [Internet]. Mar. U.S. Department of Energy, Washington D.C.. Available from: https://www.energy.gov/sites/prod/files/2014/04/f14/20140328_SEAB_TF_FracFocus2_Report_Final.pdf
US EPA, 2014. UIC program guidance [Internet] [cited 2022 May 13]. Available from: https://www.epa.gov/uic/uic-program-guidance.
US EPA, 2015a. Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources (External Review Draft). U.S. Environmental Protection Agency, Washington, D.C.
US EPA. National Primary Drinking Water Regulations [Internet]. 2015 [cited 2022 Feb 23]. Available from: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.
US EPA. Drinking Water Contaminant Human Health Effects Information [Internet]. 2015 [cited 2022 May 2]. Available from: https://www.epa.gov/sdwa/drinking-water-contaminant-human-health-effects-information.
US EPA, 2016. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report). US EPA, Washington, D.C.. Report No.: EPA/600/R-16/236F.
Varvastian, S., Kalunga, F., 2020. Transnational corporate liability for environmental damage and climate change: reassessing access to justice after Vedanta v. Jul Lungowe. Transnatl. Environ. Law. 9 (2), 323–345.
Vidic, R.D., Brantley, S.L., Vandenbossche, J.M., Yoxtheimer, D., Abad, J.D., 2013. Impact of shale gas development on regional water quality. May 17 Science 340 (6134), 1235009.
Webb, E., Bushkin-Bedient, S., Cheng, A., Kassotis, C.D., Balise, V., Nagel, S.C., 2014. Developmental and reproductive effects of chemicals associated with unconventional oil and natural gas operations. Rev. Environ. Health 29 (4), 307–318.
Wilbur, S., Jones, D., Risher, J.F., Crawford, J., Tencza, B., Llados, F., et al., 2012. Health effects. In: Toxicological Profile for 1,4 Dioxane. Agency for Toxic Substances and Disease Registry (US), Atlanta, GA [cited 2022 Oct 19]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK153671/.
Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J.J., Appleton, G., Axton, M., Baak, A., et al., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Mar 15 Sci. Data 3, 160018.
Williams, A.J., Grulke, C.M., Edwards, J., McEachran, A.D., Mansouri, K., Baker, N.C., et al., 2017. The CompTox Chemistry Dashboard: a community data resource for environmental chemistry. Dec J. Cheminf. 9 (1), 61.
Williams, A.J., Lambert, J.C., Thayer, K., Dorne, J.L.C.M., 2021. Sourcing data on chemical properties and hazard data from the US-EPA CompTox Chemicals Dashboard: a practical guide for human risk assessment. Sep 1 Environ. Int. 154, 106566.
Wiseman, H., 2009. Untested Waters: the rise of hydraulic fracturing in oil and gas production and the need to revisit regulation, 2010 Fordham Environ. Law Rev. 20 (1), 115–196.
Wylie, S.A., 2018. Fractivism: Corporate Bodies and Chemical Bonds. Duke University Press, Durham (Experimental futures: technological lives, scientific arts, anthrpological voices).
Zwickl, K., 2019. The demographics of fracking: a spatial analysis for four U.S. states. Jul 1 Ecol. Econ. 161, 202–215.