Public reporting of hydraulic fracturing chemicals in the USA, 2011–18: a before and after comparison of reporting formats

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Lancet Planet Health 2020; 4: e178–85

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Summary

Background **Hydraulic fracturing often involves the injection of millions of gallons of fracturing fluids into underground shales to extract oil and natural gas, raising health concerns over potential water contamination. Many state and federal governmental agencies rely on the third-party FracFocus online registry for disclosure of chemical ingredients in fracturing fluids, but withholding chemicals as trade secrets is common. In 2016, a new format, known as the systems approach was widely encouraged as a method of reducing withholding by decoupling disclosed chemicals from their functions, protecting against reverse-engineering of fracture fluid formulas by competitors. In this study, we assess the extent to which elevated use of the systems approach in FracFocus version 3.0 translated into greater chemical disclosure.**

Methods **We analysed 108 137 disclosure forms submitted to FracFocus between Jan 1, 2011, and Dec 31, 2018, to estimate the effect of expanded use of the systems approach on chemical withholding. We compared the proportion of forms withholding at least one chemical ingredient across time, between approaches, and by state and drilling operator.**

Findings **Since the 2016 expansion of the systems approach, 15 677 (82%) of systems approach forms have withheld an ingredient. 13 462 (89%) of 15 062 traditional FracFocus version 3.0 forms withheld an ingredient. In the quarter following the transition (July, to September, 2016), 1211 (93%) of 1304 traditional forms withheld an ingredient, compared with only 958 (76%) of 1262 systems approach forms. However, withholding rates increased throughout 2017 and, by 2018, 6949 (87%) of 8016 systems approach forms were withholding ingredients. At the end of our analysis period in the fourth quarter of 2018, systems approach forms had even greater withholding (903 [88%] of 1025 forms) than did traditional forms (855 [85%] of 1004 forms). We did not find that states or operators that submitted more systems approach forms had lower withholding.**

Interpretation **The systems approach has not reduced FracFocus chemical withholding, which continues to occur in around 87% of well fracture disclosures. FracFocus might not be an appropriate substitute for regulatory action, and measures are urgently needed for environmental and public safety.**

Funding **University of Chicago Argonne National Laboratory Seed Grant.**

Introduction

Driven by unconventional oil and gas extraction, the USA became the world's largest crude oil producer in 2018[1] and has been the largest natural gas producer since 2012.[2] This growth has been enabled by technological advances in horizontal drilling and high-volume hydraulic fracturing, which often involves injection of millions of gallons of fracturing fluids into underground tight rock formations.[3] This rapid advent of unconventional oil and gas activity has generated public concern over the potential costs to citizens, including risks to local water quality.[4]

Analyses of ground and surface water samples near hydraulic fracturing sites have identified chemicals and by-products associated with hydraulic fracturing fluids and wastewater, including volatile organic compounds[5,6] and halides,[7,8] with spills and leakage representing possible contaminant pathways.[9–11] In 2016, the US Environmental Protection Agency (EPA) published a report on several mechanisms through which hydraulic fracturing fluids and associated wastewater might impact water supplies.[12] Furthermore, the EPA compiled oral toxicity data for chemicals in hydraulic fracturing fluids and found that 986 (91%) of 1084 did not have the evidence required to identify maximum safe chronic oral reference dose values.

Since the hydraulic fracturing industry is exempt from the US Safe Drinking Water Act, which might have offered other mechanisms for obtaining chemical data,[13] the EPA assessed chemical hazards by relying heavily on FracFocus, a hydraulic fracturing chemical disclosure database developed by the Groundwater Protection Council and the Interstate Oil and Gas Compact Commission (IOGCC) in 2011.[14] By our count of the IOGCC 2015 membership roster, at least 258 (59%) of 439 members were part of or provided services to the oil

Research in context

Evidence before this study

Academic and governmental research into hydraulic fracturing has shown high levels of withholding of fracture fluid ingredients to FracFocus, a third-party public registry used by oil and gas companies, which is exempt from federal oversight. Evidence has suggested potential contamination routes for fracture fluids into ground and surface water, posing a risk to human health and emphasising the need for greater chemical disclosure by the industry. Based on preliminary evidence, a new method of disclosure known as the systems approach was introduced to encourage chemical disclosures. However, no studies have evaluated the systems approach since its widespread implementation in 2016 as the default method of disclosure in FracFocus.

We searched Google Scholar and PubMed for studies on hydraulic fracturing chemical reporting, published in English between Jan 1, 2011, and Jan 1, 2020. Our search terms included combinations of "FracFocus", "hydraulic fracturing", "fracking", "chemical reporting", "disclosure", "withholding", and "systems approach". Although many studies used FracFocus as a data source, only one study was identified that analysed FracFocus data quality and chemical withholding, and this did not include data from FracFocus version 3.0, the version in which the systems approach became widely used. No studies investigated chemical withholding in relation to the method of submission (ie, the systems approach).

Added value of this study

In versions of FracFocus before 2016, only 1036 (1·4%) of 73 899 version 2.0 disclosures were made using the systems approach. We analysed 3 years of disclosure data after the release of FracFocus version 3.0 release in 2016, which encouraged hydraulic fracturing operators to submit disclosure forms using the systems approach. After the 2016 update, 19 176 (56·0%) of 34 238 FracFocus version 3.0 submissions used this approach, enabling us to evaluate the approach and determine whether chemical withholding reduced as hoped.

Implications of all the available evidence

This study challenges the systems approach as an effective method of reducing chemical withholding in fracture fluid disclosures. Although preliminary evidence suggested marked differences between the withholding rates of systems approach disclosures and disclosures using the traditional method, our findings show that this difference was short-lived and among few operators. Encouragement of the systems approach has not been effective for reducing chemical withholding, precluding researchers and the public from being able to assess and address possible threats to the environment and public health from potentially toxic chemicals.

and gas industry; the remainder were mostly state government employees.[15] FracFocus is viewed as a regulatory tool, despite industry involvement, evidenced by at least 17 states requiring reporting to it. Furthermore, environmental and health research frequently depend upon FracFocus for hydraulic fracturing chemical use information.[16–21]

Despite the central role of FracFocus in environmental and public health policy, relatively little is understood about the quality of chemical information that is withheld or disclosed on this platform. Konschnik and Dayalu[22] did the only academic examination to date of FracFocus data quality and found the registry to contain gaps in disclosure and data inconsistencies. A US Department of Energy (DOE) review concluded that FracFocus had "greatly improved public disclosure quickly," but noted a large fraction of forms withheld at least one ingredient, primarily on confidential, proprietary, or trade secret grounds.[23] Both Konschnik and Dayalu[22] and the US DOE[23] assessed FracFocus version 2.0, the active version from 2013 to 2016. Importantly, both expressed hope that a new method of disclosure—the systems approach—would help minimise withholding rates in future versions. FracFocus itself indicated in 2015, that the systems approach would "improve chemical reporting transparency,"[24] and the systems approach was connected to at least one publicised greater disclosure initiative by Baker Hughes, a major service company.[25] Fracture fluids are typically made of water, proppant, and chemical additives, which are often mixtures of different chemicals and marketed by service companies. In traditional submissions, each disclosed additive is attached to a list of its chemical ingredients. By contrast, the systems approach enables operators to submit separate lists of additives and chemical ingredients, without linking particular chemicals to additives. For example, Halliburton markets a corrosion inhibitor additive called HAI-404M, comprised of 1-(benzyl)quinolinium chloride, isopropanol, methanol, and other chemicals.[26] In a traditional form, the HAI-404M additive would be named with its constituent chemicals, as above. In a systems approach form, HAI-404M would be listed as a corrosion inhibitor, but its constituent chemicals would appear among a separate list containing all chemicals from any injected additive. In either approach, constituent chemicals could be withheld, but the systems approach is meant to prevent reverse engineering of additive formulas while enabling disclosure of constituent chemicals.[27]

The systems approach was available in FracFocus version 2.0 but was an opt-in alternative and only used by 1036 (1%) of 73 899 forms. In 2016, FracFocus transitioned to version 3.0, which instead defaults submissions to the systems approach, although operators can still choose to submit traditional forms.[28] 19 176 (56%) of 34 238

FracFocus version 3.0 forms used the systems approach. In this study, we assessed the extent to which elevated systems approach use in FracFocus version 3.0 translated into greater chemical disclosure.

Methods

Data preparation

We acquired the complete, publicly available database of FracFocus submissions as of Jan 15, 2019.[14] Data on 4 159 917 chemical records across 152 476 submitted disclosure forms were downloaded in compressed comma-separated values format. We refer to a form as a single FracFocus job submission. Forms include multiple additives; each additive might be composed of several chemicals. The data preparation methods in this section, including data exclusions and identification of systems approach forms, were designed by Konschnik and Dayalu,[22] who used an earlier download of FracFocus data.

Between Jan 1, 2011, and May 31, 2013, forms were submitted through FracFocus version 1.0. In our download, version 1.0 forms did not contain information on individual chemical ingredients, such as their names and purposes. Therefore, we restricted our analyses to FracFocus version 2.0 and version 3.0 submissions, although we included retrospective version 2.0 submissions for past jobs occurring since Jan 1, 2011. Furthermore, we excluded duplicate submissions, which were probable errors, and any remaining forms indicating fracture dates before Jan 1, 2011. Finally, well data included longitude and latitude data under one of three projection systems (NAD27, NAD83, WGS84). We converted NAD27 coordinates to NAD83 coordinates and required that these fell within the reported state. We excluded 49 forms that reported mismatches between geographical coordinates and reported state (<1%).

We identified entry errors and invalid chemicals by cross-referencing each identifying Chemical Abstracts Service (CAS) number against seven different chemical databases (US National Library of Medicine ChemID*plus*, United States Environmental Protection Agency Substance Registry Services, ChemNet, US National Institute of Standards and Technology Chemistry WebBook, Common Chemistry, Merck, and SciFinder). Invalid chemicals were considered undisclosed and contributed to the withholding rate.

Systems approach forms were identified as those that included the phrase "listed below" (or variations thereof) under a CAS number or ingredient (chemical) name field. We inspected identifications to ensure accuracy and completeness of our classifications.

Our final analysis set included 108 137 forms, 73 899 submitted to FracFocus version 2.0 and 34 238 submitted to FracFocus version 3.0. All datasets, code, and a detailed description of data cleaning steps are publicly available online.[29] Data cleaning and analyses were done using R version 3.5.1.

Identification of chemical withholding

3 115 886 (82%) of 3 818 187 chemicals reported in the forms we analysed were valid, identifiable chemicals, 681 282 (18%) were marked proprietary, confidential, trade secret, or not available, and 21 019 (1%) appeared to be entry errors or otherwise invalid. However, although each validly disclosed chemical represents one identifiable CAS number, withheld entries might represent either a single chemical or a group of multiple chemicals that might have contributed several lines of data if disclosed (eg, surfactant mixture). For this reason, we could not know how many undisclosed CAS numbers are encapsulated by the reported number of withheld ingredients.

Therefore, we assigned a binary withholding flag to each form that withholds one or more chemicals. Unlike a percentage of withheld chemicals, this binary metric of withholding does not rely on the true number of different chemicals used in a fracture job. Additionally, a single withheld chemical on a form can be hazardous for public health. Therefore, the withholding rate is defined as the fraction of forms without complete disclosure.

Withholding and systems approach analysis

To study time trends of the withholding rate, we calculated quarterly withholding rates for three different subsets of forms: systems approach forms, traditional forms, and the entire set. As FracFocus announced and implemented FracFocus version 3.0 features over an extended period, with little news coverage, exact transition dates between version 2.0 and version 3.0 were unclear. We confirmed our April, 2016, transition date (figure 1) in the following two ways: by a press release from FracFocus on April 12, 2016, reporting the soon-to-come switch,[30] and by empirical confirmation of the first majority replacement of FracFocus version 2.0 submissions by version 3.0 forms, occurring in April, 2016 (appendix p 2). This empirical date was only used to mark the transition point visually; for quantitative analyses, we relied on the inherent FFVersion field, containing either 2 or 3.

See Online for appendix

Analysis of FracFocus states and operators

For all states represented in our FracFocus analysis set, we did a legislative review and identified chemical disclosure requirements for hydraulic fracturing operations, whether FracFocus submission was required, and the effective date of any such requirements. All information was available through websites of state government departments of environmental protection, or oil and gas divisions, except for Nebraska, where we obtained information from the department by phone. When analysing statewide disclosure statistics, we excluded jobs occurring before the state legal requirement's effective date, if applicable.

In our data, we grouped FracFocus version 3.0 forms by state and operator, restricting analyses separately to the ten states with the most submissions (encompassing 32 834 [96%] forms) and ten operators with the most

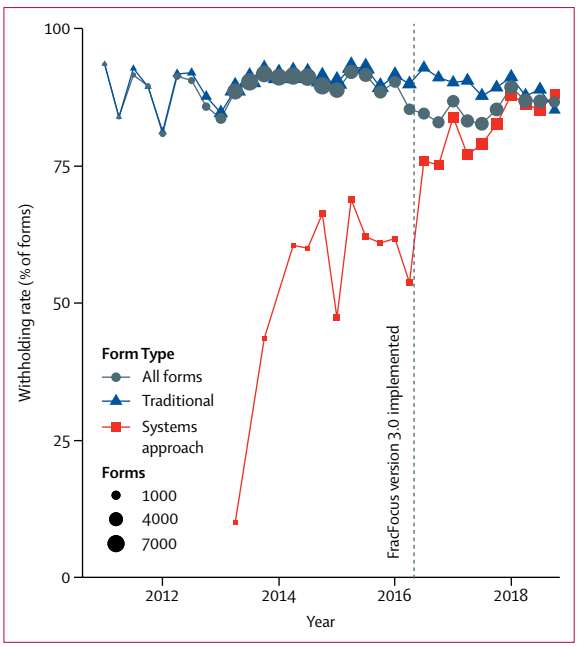

Figure 1: **Quarterly FracFocus withholding rates before and after version 3.0**
Withholding rates were calculated as the percentage of forms lacking full chemical disclosure. Quarters with less than 30 submitted jobs are omitted from display. The dashed line marks April 12, 2016, which matches empirical evidence of the majority transition to FracFocus version 3.0.

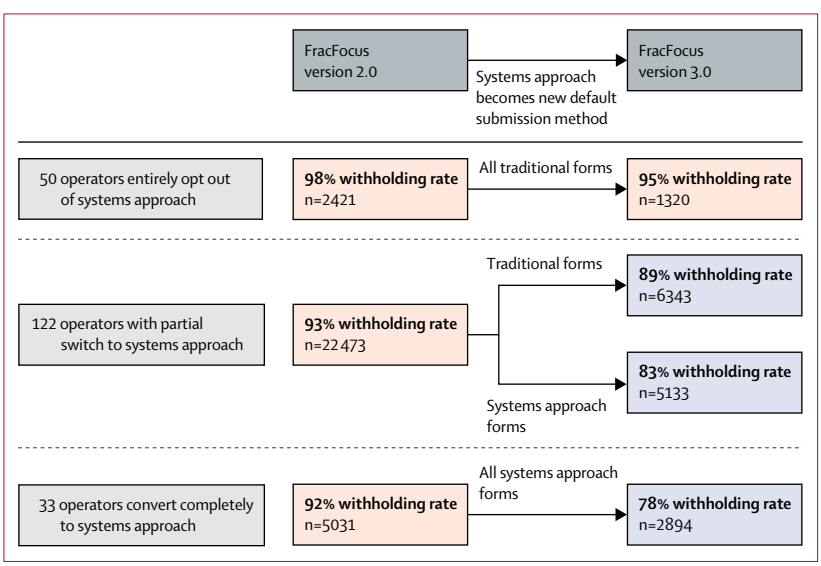

Figure 2: **Withholding rates among new systems approach users in FracFocus version 3.0**
Operators were limited to those with at least five forms each in both FracFocus version 2.0 and version 3.0, and to those who had never used the systems approach in FracFocus version 2.0. Operators were then divided based on the extent of conversion to the systems approach in FracFocus version 3.0, into those who continued to opt out entirely of the new systems approach, choosing the traditional approach for all submissions; those who opted out on some submissions but used the systems approach for other forms; or those who converted completely to the new systems approach. Withholding rates are presented among each group of operators. Blue boxes indicate rates calculated among systems approach forms and red boxes indicate traditional forms.

submissions (8426 [25%] forms). We calculated statewide and operator-wide use of the systems approach to observe variability in uptake of the new method, particularly since states or operators might have different policies that influence disclosure. Finally, we binned forms by state and operator (eg, EOG Resources in Texas) to understand the association between systems approach uptake and withholding rates.

Description of chemical toxicity

Among FracFocus version 3.0 forms, we evaluated disclosure frequencies of a list of chemicals with potential toxicological importance, as identified in the EPA 2016 report.[12] Among those that have known chronic oral toxicity (reference dose) values, we selected the eight chemicals identified by the EPA in at least 10% of disclosures, and the ten chemicals with the lowest reference dose values, according to a summary publication.[31] The reference dose value of a chemical is used by the EPA to identify the maximum safe daily exposure below which there is no appreciable risk of adverse effects among individuals or populations.[32] For each of these chemicals, we presented reference dose values, critical health effects from the literature, and the percentage of FracFocus version 3.0 forms that disclose its use, stratified by the systems approach. These rates of use might underestimate actual chemical use because of chemical withholding.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

Among the few FracFocus version 2.0 forms that opted into the systems approach before April, 2016, only 583 (56%) of 1036 withheld an ingredient, which motivated anticipation over expansion of the systems approach.[12,22] However, 72 863 (92%) of 73 899 FracFocus version 2.0 forms used the traditional approach; 66 177 (91%) of these 72 863 forms withheld an ingredient. By contrast, 19 176 (56%) of 34 238 FracFocus version 3.0 forms used the systems approach. Among these, 15 677 (82%) withheld an ingredient. 13 462 (89%) of 15 062 traditional FracFocus version 3.0 forms withheld an ingredient.

Although the aggregated numbers appear somewhat encouraging, a different picture emerged when we studied this shift over time. We grouped forms by their fracture dates and observed quarterly withholding rates among each approach (figure 1). Empirically, the FracFocus version 2.0 to version 3.0 transition appears to have occurred in April, 2016; a more precise date is unknown because form submission dates were not available (appendix p 2). Before October, 2014, no quarters included more than 40 systems approach forms. By contrast, every quarter after the transition received over 1000 systems approach forms.

In the quarter following the transition (July, to September, 2016), 1211 (93%) of 1304 traditional forms withheld an ingredient, compared with only 958 (76%) of 1262 systems approach forms. However, withholding rates increased throughout 2017 and, by 2018, 6949 (87%) of 8016 systems approach forms were withholding ingredients. At the end of our analysis period in the fourth quarter of 2018, systems approach forms had even greater withholding (903 [88%] of 1025 forms) than did traditional forms (855 [85%] of 1004 forms). This reversal suggests that, although the systems approach might have initially appeared a salient option for improving public reporting of fracture fluid chemicals, its effect has been marginal at best and ultimately might not be better than traditional disclosure.

Since operators are still given the choice between traditional and systems approach submissions in FracFocus version 3.0, we tracked operator-specific withholding rates across the transition to compare each approach (figure 2). To study new systems approach users, we excluded 116 (9%) of 1321 operators that were using the systems approach before the transition; we also excluded 569 (43%) operators with fewer than five forms in either FracFocus version 2.0 or version 3.0. We then categorised each operator into one of three FracFocus version 3.0 behaviours, as follows: those who continued to opt out entirely of the new systems approach default, choosing the traditional approach for all submissions; those who opted out on some submissions but used the systems approach for other forms; or those who converted completely to the new default systems approach. We calculated aggregated withholding rates across operators in each category.

Operators in the second and third categories presented lower withholding rates among their new FracFocus version 3.0 systems approach forms than among their version 2.0 traditional forms, by around 9 and 14 percentage points, respectively. Operator companies that continued to opt out of the systems approach in FracFocus version 3.0 also had a drop in withholding of about 3 to 4 percentage points, a reduction also evident among the traditional forms of operators who began using a mix of systems approach and traditional methods. This result indicates that a small drop in withholding might have occurred, even in the absence of the FracFocus version 3.0 systems approach expansion. A possible explanation for this general reduction in withholding is the introduction of technical upgrades to FracFocus version 3.0, including error messages when invalid CAS numbers are entered into submission forms.[22,28]

We binned submissions by operator and state to evaluate the overall relationship between systems approach use and disclosure across groups with distinct policies. 16 (62%) of 26 states (Alaska, Alabama, Colorado, Kentucky, Michigan, North Dakota, Nebraska, New Mexico, Nevada, Oklahoma, Pennsylvania, South Dakota, Texas, Utah, Virginia, and West Virginia) in our data require submission to FracFocus for any hydraulic fracturing operation, whereas five others (Kansas, Louisiana, Mississippi, Montana, and Ohio) allow a choice of submission between FracFocus and an alternative disclosure platform (appendix p 1). State systems approach use and withholding rates vary widely, although states with intensive hydraulic fracturing tend to have more withholding (appendix p 3). Among states with at least 100 FracFocus version 3.0 form submissions, New Mexico (1538 [94%] of 1639 forms) and North Dakota (2542 [91%] of 2792 forms) had the highest withholding rates, whereas Virginia (139 [49%] of 281 forms) and California (0 of 370 forms) had the least withholding. Notably, Virginia and California were the only states where all forms used the systems approach.

To evaluate whether state-wide or company-wide movement toward the systems approach might correlate with lower withholding rates, we binned submissions for the ten states and operators with the most FracFocus version 3.0 forms and calculated withholding rates per operator, per state. Despite widely differing use of the

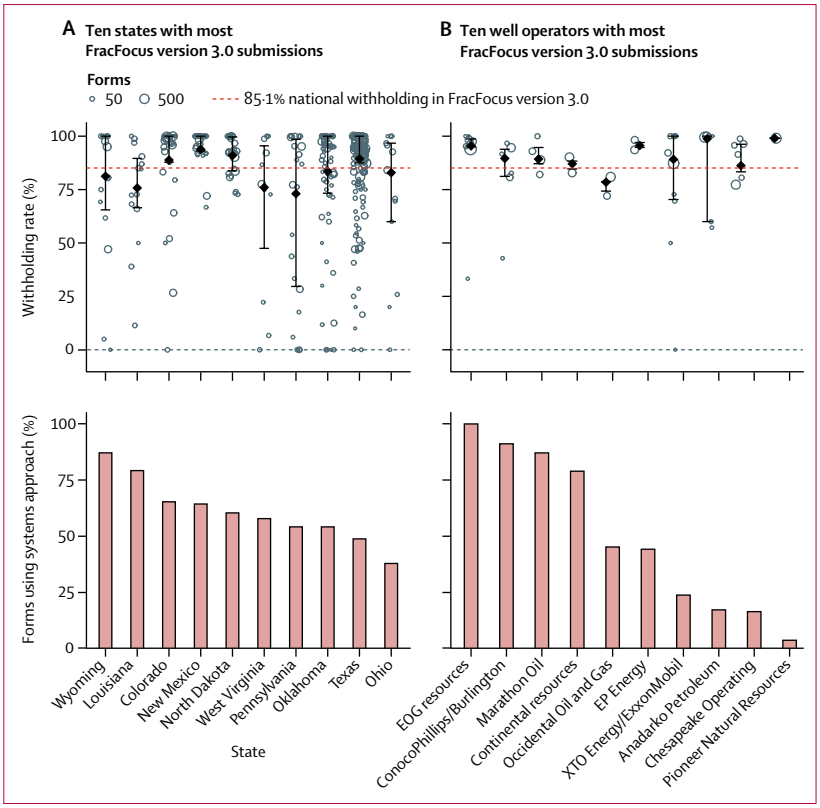

Figure 3: **Systems approach use and withholding rates among largest states and well operating companies**
FracFocus version 3.0 submissions are grouped by state and operator company. Each point in the upper panels represents the withholding rate of one such state or operator group; larger points indicate more forms (hydraulic fracturing jobs) within the group. The dashed line marks the 85·1% mean withholding rate across all FracFocus version 3.0 forms. (A) The ten largest hydraulic fracturing states in FracFocus version 3.0 are arranged by decreasing systems approach use. Black diamonds indicate statewide weighted mean withholding rates and bars show the unweighted IQR for operator withholding rates within the state. (B) The ten largest well operators in FracFocus version 3.0 are arranged by decreasing systems approach use. Black diamonds represent the operator overall withholding rate and bars indicate the unweighted IQR across states in which the operator works.

	Chemical Abstracts Service number	Reference dose (mg/kg/day)[31]	Critical effect[31]	Traditional forms (n=15 062)	Systems approach forms (n=19 176)	Overall (all forms; n=34 238)
Methanol	67-56-1	2	Extra cervical ribs (developmental)	11 155 (74·1%)	13 183 (68·7%)	24 338 (71·1%)
Ethylene glycol	107-21-1	2	Kidney toxicity	7471 (49·6%)	6941 (36·2%)	14 412 (42·1%)
Propargyl alcohol	107-19-7	0·002	Renal and hepatotoxicity	4171 (27·7%)	5181 (27·0%)	9352 (27·3%)
2-butoxyethanol	111-76-2	0·1	Haemosiderin deposition in the liver	3726 (24·7%)	2012 (10·5%)	5738 (16·8%)
Naphthalene	91-20-3	0·02	Decreased terminal bodyweight	620 (4·1%)	3608 (18·8%)	4228 (12·3%)
Quaternary ammonium compounds	68424-85-1	0·44	Decreased bodyweight and weight gain	3702 (24·6%)	5506 (28·7%)	9208 (26·9%)
Formic acid	64-18-6	0·9	Reproductive toxicity	2426 (16·1%)	1808 (9·4%)	4234 (12·4%)
Sodium chlorite	7758-19-2	0·03	Neurodevelopmental effects	968 (6·4%)	3340 (17·4%)	4308 (12·6%)

The eight most common chemicals with available reference dose values were identified, along with their critical effects, from Yost and colleagues'[31] overview of US Environmental Protection Agency findings. Reference dose values represent the maximum estimated reasonably safe daily oral intake—lower values imply greater oral toxicity. Cancer effects were not considered. Counts represent the number of FracFocus version 3.0 forms in each method that disclosed the specified chemical.

Table 1: **Disclosure rates of common chemical constituents in FracFocus disclosures**

	Chemical Abstracts Service number	Reference dose (mg/kg/day)[31]	Critical effect[31,44]	Traditional forms (n=15 062)	Systems approach forms (n=19 176)	Overall (all forms; n=34 238)
Arsenic	7440-38-2	0·0003	Hyperpigmentation, keratosis, and vascular effects	0	22 (0·11%)	22 (0·06%)
Phosphine	7803-51-2	0·0003	Decreased body weight	0	0	0
Acrolein	107-02-8	0·0005	Decreased survival (in rats)	0	0	0
(E)-crotonaldehyde	123-73-9	0·001	Unknown	0	1 (<0·01%)	1 (<0·01%)
1,2-propylene oxide	75-56-9	0·001	Nasal respiratory epithelium infolds	0	190 (1·0%)	190 (0·6%)
Acrylamide	79-06-1	0·002	Nerve degeneration	1588 (10·5%)	5935 (30·9%)	7523 (22·0%)
Benzyl chloride	100-44-7	0·002	Unknown	150 (1·0%)	225 (1·2%)	375 (1·1%)
Propargyl alcohol	107-19-7	0·002	Renal and hepatotoxicity	4171 (27·7%)	5181 (27·0%)	9352 (27·3%)
Chromium(VI)	18540-29-9	0·003	Unknown	0	0	0
Benzene	71-43-2	0·003	Decreased lymphocytes	9 (0·06%)	1 (<0·01%)	10 (0·03%)

The ten hydraulic fracturing-related chemicals with the lowest reference dose values were identified from Yost and colleagues'[31] overview of the US EPA findings. Critical effects were identified through the EPA Integrated Risk Information System.[44] Among these ten chemicals, phosphine, acrolein, and chromium(VI) were not disclosed in FracFocus version 3.0. Cancer effects were not considered. Counts represent the number of FracFocus version 3.0 forms in each method that disclosed the specified chemical. EPA=Environmental Protection Agency.

Table 2: **Disclosure rates of chemicals with greatest oral toxicity**

systems approach in FracFocus version 3.0, particularly between operators, withholding rates among those states or operators are relatively similar to the version 3.0 national withholding rate of 85% (34 238 forms; figure 3). The Pearson correlation coefficient between withholding rate and systems approach use was –0·12 for states and –0·19 for operators.

We analysed disclosure frequencies of specific chemicals identified in the EPA investigation of hydraulic fracturing chemicals,[12] focusing on the following two categories: particularly abundant chemicals (table 1) and particularly toxic chemicals (table 2). Table 1 presents the eight chemicals identified by the EPA in at least 10% of pre-2013 hydraulic fracturing job submissions that they analysed, among those chemicals that have chronic oral toxicity reference dose values available. Table 2 includes the ten chemicals in the EPA report with the lowest reference dose values, corresponding to the greatest oral toxicities. Additionally, we show the percentage of FracFocus version 3.0 forms disclosing these chemicals, stratified by traditional and systems approaches. Many toxic chemicals identified by the EPA, including phosphine, acrolein, and chromium(VI), do not appear in any FracFocus version 3.0 submissions. Methanol is the most frequently disclosed chemical with an available reference dose value, present in 24 338 (71%) of 34 238 FracFocus version 3.0 forms. There was no immediately apparent trend in chemical disclosure between the traditional and systems methods; some chemicals, such as acrylamide and naphthalene, appear substantially more frequently in systems approach forms than in traditional forms, whereas others, including 2-butoxyethanol and ethylene glycol, show the reverse trend. Crucially, because of withholding, the percentages shown in tables 1 and 2 might underestimate actual chemical use and cannot capture undisclosed information.

Discussion

The systems approach has been promoted by members of the academic, government, and industry communities as a way of minimising chemical withholding rates while preventing reverse engineering of proprietary

hydraulic fracturing fluid formulas.[12,22,27] We exploited the sudden shift toward greater systems approach use after the introduction of FracFocus version 3.0 to study whether withholding rates dropped, as has been anticipated. We found that, although markedly increased use of the systems approach appeared to improve disclosure in 2016 after the FracFocus version 3.0 transition, by the end of our study period in 2018, withholding rates remained high and no longer differed between the systems approach and traditional forms. Even the brief improvements in disclosure during the 2016 transition are small from a public knowledge perspective. The slight reduction overall in withheld forms that occurred in FracFocus version 3.0 might be due to factors other than increased systems approach use, for example, new warnings during the submission process.

Despite the gaps in chemical disclosure to FracFocus, our review of state legislation found that at least 22 states legally require or recommend disclosure, with many states depending exclusively upon FracFocus for this information. California was the only state with a 0% withholding rate in FracFocus version 3.0; notably, all 370 of its forms used the systems approach. On Jan 1, 2016, California launched its own mandatory reporting system, with stricter requirements than FracFocus. Unlike FracFocus, which gives operators a choice between the systems approach and traditional submission methods, California's system only accepts submissions using the systems approach model, with additives and their constituent chemicals both reported but unlinked. California requires mandatory disclosure of all hydraulic fracturing fluid constituents and their CAS numbers to the Department of Conservation, even if a trade secret is claimed.[33] This approach might serve as a model for other states with an interest in developing a public chemical disclosure platform and warrants further study. Although Pennsylvania wrote a similar state-specific chemical registry into law in 2012, the public-facing site was never released.[34]

Our study focused on hydraulic fracturing ingredient disclosure because of the potential public health and environmental impacts associated with some chemical additives. Over the past 5 years, a small but growing body of literature has linked local hydraulic fracturing activity to health outcomes. Birth outcomes have been most widely studied, finding significant associations between local hydraulic fracturing and low birthweight[35–37] and preterm birth.[38,39] Studies have also suggested an effect on increased cardiology and neurology hospitalisations,[40] pneumonia,[41] and skin and genitourinary diseases.[42] Proposed mechanisms also include outdoor air pollution and changing worker demographics, but water contamination remains an understudied possibility, and accurately tracing such health outcomes to particular chemical exposures is not possible without reliable and complete disclosure information.

FracFocus version 1.0 submissions were the only source providing chemical frequencies and geographical locations of chemical use for the EPA, highlighting the extent of the federal government's reliance on FracFocus.[12] Despite toxic additives, such as acrylamide or propargyl alcohol, composing less than 1% of fracture fluids, their volumes might number in the tens of thousands of gallons per well,[43] presenting an appreciable risk for water contamination, including through spills, leakage, or waste disposal.[44] Importantly, among fully disclosed chemicals, a majority were not found by the EPA in its Integrated Risk Information System[45] or in five other chemical databases, indicating that the potential oral toxicity of many of these chemicals has not been sufficiently studied. Accurate and complete disclosures might help researchers identify and prioritise chemicals in need of comprehensive investigations, whereas non-disclosure might further compound this problem.

The primary limitation of our study was the missing denominator of total chemicals, caused by uncertainty about how many separate chemicals operators might have included under each withheld ingredient. This constrained our analyses to treat forms withholding one chemical identically to forms withholding dozens. Furthermore, our withholding measure assumed no ingredients were entirely unlisted, which would be a step beyond withholding.

In conclusion, health risks to local communities are crucial considerations for energy policy makers and chemical reporting requirements in the hydraulic fracturing industry are insufficient to draw reliable or useful conclusions. In a system that exempts full chemical disclosure, the systems approach might not reduce withholding, despite high anticipation. A centralised, accurate, and complete chemical disclosure registry is urgently needed to enable greater academic and public study of health and environmental outcomes. Our analysis indicates FracFocus might not be an appropriate regulatory tool for safeguarding the environment and public health; a central government role could be required to protect all stakeholder interests.

For more on **reporting and disclosures in California** see https://wellstar-public.conservation.ca.gov/

Contributors
PS supervised all analyses and helped write the manuscript. KT did the data analysis and helped write the manuscript. NH researched state and federal regulations around chemical disclosure of hydraulic fracturing fluids.

Declaration of interests
We declare no competing interests.

Acknowledgments
PS was funded by a University of Chicago Argonne National Laboratory Seed Grant. KT and NH were funded by University of Chicago undergraduate research fellowships.

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