Towards an understanding of the environmental and public health impacts of shale gas development: an analysis of the peer-reviewed scientific literature, 2009-2014

Introduction

Conversations on the negative environmental and public health impacts of shale gas development continue to play out in the media, in policy discussions, and among the general public. But what does the science actually say? While research continues to lag behind the rapid scaling of shale gas development, there has been a surge of peer-reviewed scientific papers published in recent years. In fact, of all the available scientific peer-reviewed literature on the impacts of shale gas development, approximately 73% has been published since January 1, 2013. What this tells us is that the scientific community is only now beginning to understand the impacts of this industry on the environment and human populations. Hazards and risks have been identified, but many data gaps still remain. Importantly, there remains a dearth of quantitative epidemiology that assesses associations between risk factors and human health outcomes among populations.

Still, there is now a lot more known about the impacts of shale gas development than when New York's *de facto* moratorium went into effect. This analysis is intended to provide an overview of what is currently known about the potential impacts of shale gas development on human health and the environment. We include only the published peer-reviewed literature available on the subject. Specifically, this analysis uses studies relevant to near-term and long-term population health in communities experiencing shale gas development.

As the industry continues to expand in other parts of the country, New York has been in a unique position to learn from experiences and research in places like Pennsylvania, Texas, and Colorado. Clearly, this is a complex, polarizing issue and one that likely requires more than simply empirical evidence to create sound policy decisions. Yet, New York should pay close attention to the actual experiences and evidence arising out of other parts of the country that have opened their borders to shale gas development.

There are limitations to this analysis and it provides just a snapshot of what we know scientifically about the public health hazards, risks, and impacts associated with shale gas development. Furthermore, this document is preliminary and has not yet been subjected to external peer review. Nonetheless, it should provide readers with a general sense of the existing body of scientific literature on shale gas development.

Methods

Database assemblage and review

This analysis was conducted using the PSE Study Citation Database (available at: http://psehealthyenergy.org/site/view/1180). This near exhaustive collection of peer-reviewed literature on shale gas development was broken into 12 topics that attempt to organize the studies in a useful and coherent fashion. These topics include air quality, climate, community, ecology, economics, general (comment/review), health, regulation, seismicity, waste/fluids, water quality, and water usage. This collection was assembled over several years using a number of different search strategies, including the following:

- Systematic searches in scientific databases across multiple disciplines: PubMed (http://www.ncbi.nlm.nih.gov/pubmed/), Web of Science (http://www.webofknowledge.com), and ScienceDirect (http://www.sciencedirect.com)
- Searches in existing collections of scientific literature on shale gas development, such as the Marcellus Shale Initiative Publications Database at Bucknell University (http://www.bucknell.edu/script/environmentalcenter/marcellus), complemented by Google (http://www.google.com) and Google Scholar (http://scholar.google.com)
- Manual searches (hand-searches) of references included in all peer-reviewed studies that pertained directly to shale gas development.

For bibliographic databases, we used a combination of Medical Subject Headings (MeSH)-based and keyword strategies, which included the following terms, as well as relevant combinations:

> shale gas, shale, hydraulic fracturing, fracking, drilling, natural gas, air pollution, methane, water pollution, public health, water contamination, fugitive emissions, air quality, climate, seismicity, waste, fluids, economics, ecology, water usage, regulation, community, epidemiology, Marcellus, Barnett, Denver-Julesberg Basin, unconventional gas development, and environmental pathways.

This database and subsequent analysis excluded technical papers on shale gas development not applicable to determining potential environmental and public health impacts. Examples include papers on optimal drilling strategies, reservoir evaluations, estimation algorithms of absorption capacity, patent analysis, and fracture models designed to inform stimulation techniques. Because this collection is limited to papers subjected to external peer-review in the scientific community, it does not include government reports, environmental impact statements, policy briefs, white papers, law review articles, or other grey literature. This database also does not include studies on coalbed methane, coal seam gas, tar sands or other forms of fossil fuel extraction (offshore drilling, etc.).

We have tried to include all literature that meets our criteria in our collection of the peer-reviewed science, however, it is possible that some papers may have gone undetected. Thus, we refer to the collection as *near* exhaustive. We are sure, however, that the most seminal studies on the public health dimensions of shale gas development in leading scientific journals are included. The PSE Healthy Energy database has been used and reviewed by academics and experts throughout the U.S. and internationally and has been subjected to public and professional scrutiny before and after this analysis. It represents the most comprehensive public collection of peer-reviewed scientific literature on shale gas development in the world and has been accessed by thousands of people. Many of the publications in this database can be found in a review paper,

published in the peer-reviewed journal, *Environmental Health Perspectives*, authored by Shonkoff et al. (2014) (http://ehp.niehs.nih.gov/wp-content/uploads/advpub/2014/4/ehp.1307866.pdf).

Scope of analysis & inclusion/exclusion criteria

There has been great confusion about environmental dimensions of shale gas development or "fracking" because of the lack of uniform, well-defined terminology and boundaries of analysis. The public and the media use the term fracking as an umbrella term to refer to the entirety of shale gas development, including processes ranging from land clearing to well stimulation, to waste disposal. On the other hand, the oil and gas industry and many in the scientific community generally use the term as shorthand for one particular type of well stimulation method used to enhance the production of oil and natural gas – hydraulic fracturing.

The PSE Healthy Energy database and this analysis are both concerned with shale gas development in its entirety, enabled by hydraulic fracturing, and not just the moment of hydraulic fracturing well stimulation, which should have a limited role in sound policy discussions. If we are to understand the social, environmental, and public health dimensions of shale gas development we must look beyond only the moment of well stimulation, especially when the scientific literature indicates other aspects of the overall process warrant concern. Thus, this project can be viewed as an analysis of the scientific literature on hydraulic fracturing *and* its associated operations and ancillary infrastructure.

The focus of this analysis is, first and foremost, on the primary research on shale gas development published to date. To that extent we have only included papers that evaluate the association between shale gas development and environmental and public health impacts. As such, not all publications in the PSE Healthy Energy database were used in this analysis. We have not included the following topics in this analysis: climate, community, ecology, economics, general, regulation, seismicity, waste/fluids, and water usage. We have also not included all of the papers within the three topics we did include (health, water quality, and air quality). For instance, with the exception of public health papers, for which there has been very little primary research, we have excluded commentaries and review articles. We have also excluded those papers that provide baseline data or address research methods that do not assess impacts. We have also excluded letters to the editor of scientific journals that critique a particular study or the subsequent response of the author(s).

We have restricted the studies included in this analysis to those published between 2009 and 2014. The main reason for doing so is that scientific literature on shale gas development did not appear until around that time. There are some studies in the database on conventional forms of oil and natural gas development that are relevant to shale gas, but to maintain greater consistency we have decided to exclude those prior to 2009 from the analysis. For instance, we excluded a study published in *The Lancet* that examined the association between testicular cancer and employment in agriculture and oil and gas development published in 1986 (Sewell *et al.* 1986). Relatedly, some of the studies included in this analysis may be broader than shale gas development and could potentially include other forms of both conventional and unconventional oil and gas development. This is true for some of the top-down, field based air pollutant

emissions studies that gauge leakage rates and emission factors in Western oil and gas fields. Where studies are not specifically related to shale gas development we included them only when the findings are recent and substantially relevant.

Again, it is important to note that scientists are only beginning to understand the environmental and public health impacts of these rapidly expanding industrial practices. Our analysis represents a survey of the existing science to date in an attempt to determine the direction in which consensus is headed and to achieve a deeper understanding of the environmental and public health impacts of this form of energy development. What we know at this time is based on modeling and field-based studies on unconventional oil and gas development (primarily from shale) in parts of the United States, such as Texas, Colorado, and Pennsylvania, where the extraction of natural gas from shale formations has only relatively recently been scaled.

Categorical framework

We have created categories for each topic in an attempt to identify and group studies in ways that are both useful and intuitive. Clearly, there are limitations to this approach and many studies are nuanced or incommensurable in ways that may be inappropriate for this type of analysis. This is especially true for some topics, such as air and water quality. Further, some studies may properly be included in multiple topics and in a few cases we have done so. For instance, some studies may contain data that are relevant to both air quality and public health (Bunch et al. 2014; Colborn et al. 2014; Macey et al. 2014).

Nonetheless, in order to glean some kind of scientific overview or growing scientific consensus on the environmental public health dimensions of shale gas development that may be useful to policy determinations we strived to create the most simple and accurate approach possible. Please refer to the tables included in the appendix for citations and categorization of studies.

Topics	**Categories**
Health	• Indication of potential risks of or actual adverse health outcomes • No indication of significant risks of or actual adverse health outcomes
Water Quality	• Indication of potential, positive association, or actual incidence of water contamination • Indication of minimal potential, negative association, or rare incidence of water contamination
Air Quality	• Indication of elevated air pollution emissions and/or atmospheric concentrations • No indication of significantly elevated air pollutant emissions and/or concentrations

Health

Health outcome studies and epidemiologic investigations continue to be particularly limited and most of the peer-reviewed papers to date are commentaries and reviews. We have also separately analyzed peer-reviewed scientific commentaries because original research is still so limited for public health ("all papers"). Although commentaries should essentially be acknowledged as opinions, they are the opinions of experts formed from the available literature and have also been subjected to peer-review.

Included in this topic are papers that consider the question of public health in the context of shale gas development. Of course, research findings in other categories such as air quality and water quality are relevant to public health, but here we only include those studies that *directly* consider the health of individuals and human populations. We considered this topic and its related categories in both the context of original research and commentaries and reviews. We only consider research to be original if it measures health outcomes or complaints (i.e., not health research that attempts to determine perceptions or methods for future research agendas). The vast majority of these papers indicate the need for additional study, particularly large-scale, quantitative epidemiologic research.

Water Quality

Papers on water quality are more nuanced in that some rely on empirical field measurements, while others explore mechanisms for contamination or use modeled data to determine water quality risks. Further, some of these studies explore only one aspect of shale gas development, such as the well stimulation process enabled by hydraulic fracturing. Thus, these studies do not indicate whether or not shale gas development as a whole is associated with water contamination and are therefore limited in their utility for gauging water quality impacts. Nonetheless, we have included all original research, including modeling studies. We have excluded studies that explore only evaluative methodology or baseline assessments as well papers that simply comment on or review previous studies. Here we are only concerned with actual findings in the field or modeling studies that specifically address the risk or occurrence of water contamination.

Air Quality

Air quality is a more complex, subjective measure that beckons comparison to other forms of energy development or industrial processes. Yet, a review and analysis of the air quality data is still useful and certainly relevant to health outcomes. Although methane is a precursor to tropospheric ozone we have excluded studies that focus exclusively on methane emissions from this topic. However, studies that address methane *and* non-methane volatile organic compound (VOC) emissions have been included, given the health-damaging dimensions of a number of VOCs (i.e., benzene, toluene, ethylbenzene, xylene, etc.) and the role of VOCs in the production of tropospheric ozone, a strong respiratory irritant. Studies that have explored the health implications of air pollution emissions, atmospheric concentrations, and exposure levels are included in both this category and the public health category. The studies listed under this topic are those that specifically address air emissions and air quality from well stimulation-enabled oil and gas development (i.e., unconventional oil and gas development) at either a local or regional scale. These include local and regional measurements of non-methane volatile organic

compounds and tropospheric ozone. We only include original research for this topic, as measurement studies constitute the majority of air emission and air quality studies.

Results

Limitations

This project aims to provide an overview of existing scientific studies and findings based on the world's experience with shale gas development. While our database is, to our best estimation, exhaustive, our literature search may not have captured all relevant scientific literature. Additionally, differences in geography may render some studies less relevant when interpreted across geographic and geological space. While the majority of the studies included in this analysis are directly relevant to shale gas development, some may include data from other types of well stimulation-enabled oil and gas reservoirs, such as that from tight sands. However, because many of the processes are, for practical purposes, sufficiently similar (e.g., drilling, hydraulic fracturing, generation and disposal of waste), we have included them in this analysis.

Despite the inherent limitations in this type of analysis, our literature review provides a general idea of the weight of the scientific evidence of possible impacts that could ensue in New York State should it open its borders to shale gas development. It is important to note that this analysis only concerns itself with current empirical evidence and does not take into account developments that could potentially influence environmental and public health outcomes in positive or negative ways under different regulatory regimes. For instance, technological improvements may mitigate some existing problems, but as development continues, well pad intensities increase, and novel geologies and practices are encountered, impacts may increase.

Finally, all forms of energy production and industrial processing have environmental impacts. This report is only focused on reviewing and presenting the available science on some of the most salient environmental and public health concerns associated with shale gas development. We make no claims about the level of impacts that should be tolerated by society – these are ultimately questions of societal values.

Appendix

Health: Original Research (n = 15)

- *Indication of potential risks or adverse health outcomes (n = 13)*

1. Bamberger M, Oswald RE. 2012. Impacts of Gas Drilling on Human and Animal Health. NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy 22:51–77; doi:10.2190/NS.22.1.e.
2. Colborn T, Kwiatkowski C, Schultz K, Bachran M. 2011. Natural Gas Operations from a Public Health Perspective. Human and Ecological Risk Assessment: An International Journal 17:1039–1056; doi:10.1080/10807039.2011.605662.
3. Colborn T, Schultz K, Herrick L, Kwiatkowski C. 2014. An Exploratory Study of Air Quality near Natural Gas Operations. Human and Ecological Risk Assessment: An International Journal 0:null; doi:10.1080/10807039.2012.749447.
4. Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber WK. 2013. Occupational exposures to respirable crystalline silica during hydraulic fracturing. J Occup Environ Hyg 10:347–356; doi:10.1080/15459624.2013.788352.
5. Esswein EJ, Snawder J, King B, Breitenstein M, Alexander-Scott M, Kiefer M. 2014. Evaluation of Some Potential Chemical Exposure Risks During Flowback Operations in Unconventional Oil and Gas Extraction: Preliminary Results. Journal of Occupational and Environmental Hygiene 11:D174–D184; doi:10.1080/15459624.2014.933960.
6. Ferrar KJ, Kriesky J, Christen CL, Marshall LP, Malone SL, Sharma RK, et al. 2013. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. International Journal of Occupational and Environmental Health 19:104–112; doi:10.1179/2049396713Y.0000000024.
7. Kassotis CD, Tillitt DE, Davis JW, Hormann AM, Nagel SC. 2013. Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region. Endocrinology 155:897–907; doi:10.1210/en.2013-1697.
8. Macey GP, Breech R, Chernaik M, Cox C, Larson D, Thomas D, et al. 2014. Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. Environmental Health 13:82; doi:10.1186/1476-069X-13-82.
9. McKenzie LM, Guo R, Witter RZ, Savitz DA, Newman LS, Adgate JL. 2014. Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado. Environmental Health Perspectives 122; doi:10.1289/ehp.1306722.
10. McKenzie LM, Witter RZ, Newman LS, Adgate JL. 2012. Human health risk assessment of air emissions from development of unconventional natural gas resources. Sci. Total Environ. 424:79–87; doi:10.1016/j.scitotenv.2012.02.018.
11. Rabinowitz PM, Slizovskiy IB, Lamers V, Trufan SJ, Holford TR, Dziura JD, et al. 2014. Proximity to Natural Gas Wells and Reported Health Status: Results of a Household Survey in Washington County, Pennsylvania. Environmental Health Perspectives; doi:10.1289/ehp.1307732.
12. Saberi P, Propert KJ, Powers M, Emmett E, Green-McKenzie J. 2014. Field Survey of Health Perception and Complaints of Pennsylvania Residents in the Marcellus Shale Region. Int J Environ Res Public Health 11:6517–6527; doi:10.3390/ijerph110606517.
13. Steinzor N, Subra W, Sumi L. 2013. Investigating Links between Shale Gas Development and Health Impacts Through a Community Survey Project in Pennsylvania. NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy 23:55–83; doi:10.2190/NS.23.1.e.

- *No indication of significant risks or adverse health outcomes (n = 2)*

1. Bunch AG, Perry CS, Abraham L, Wikoff DS, Tachovsky JA, Hixon JG, et al. 2014. Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air

and potential human health risks. Science of The Total Environment 468–469:832–842; doi:10.1016/j.scitotenv.2013.08.080.
2. Fryzek J, Pastula S, Jiang X, Garabrant DH. 2013. Childhood cancer incidence in pennsylvania counties in relation to living in counties with hydraulic fracturing sites. J. Occup. Environ. Med. 55:796–801; doi:10.1097/JOM.0b013e318289ee02.

Health: All Papers (n = 47)

- *Indication of potential risks or adverse health outcomes (n = 45)*

1. Adgate JL, Goldstein BD, McKenzie LM. 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. Environ. Sci. Technol. 48:8307–8320; doi:10.1021/es404621d.
2. Bamberger M, Oswald RE. 2012. Impacts of Gas Drilling on Human and Animal Health. NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy 22:51–77; doi:10.2190/NS.22.1.e.
3. Bamberger M, Oswald RE. 2014. Unconventional oil and gas extraction and animal health. Environ. Sci.: Processes Impacts; doi:10.1039/C4EM00150H.
4. Chalupka S. 2012. Occupational silica exposure in hydraulic fracturing. Workplace Health Saf 60:460; doi:10.3928/21650799-20120926-70.
5. Colborn T, Kwiatkowski C, Schultz K, Bachran M. 2011. Natural Gas Operations from a Public Health Perspective. Human and Ecological Risk Assessment: An International Journal 17:1039–1056; doi:10.1080/10807039.2011.605662.
6. Colborn T, Schultz K, Herrick L, Kwiatkowski C. 2014. An Exploratory Study of Air Quality near Natural Gas Operations. Human and Ecological Risk Assessment: An International Journal 0:null; doi:10.1080/10807039.2012.749447.
7. Coram A, Moss J, Blashki G. 2014. Harms unknown: health uncertainties cast doubt on the role of unconventional gas in Australia's energy future. Med. J. Aust. 200.
8. Down A, Armes M, Jackson RB. 2013. Shale Gas Extraction in North Carolina: Research Recommendations and Public Health Implications. Environ Health Perspect 121:A292–A293; doi:10.1289/ehp.1307402.
9. Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber WK. 2013. Occupational exposures to respirable crystalline silica during hydraulic fracturing. J Occup Environ Hyg 10:347–356; doi:10.1080/15459624.2013.788352.
10. Esswein EJ, Snawder J, King B, Breitenstein M, Alexander-Scott M, Kiefer M. 2014. Evaluation of Some Potential Chemical Exposure Risks During Flowback Operations in Unconventional Oil and Gas Extraction: Preliminary Results. Journal of Occupational and Environmental Hygiene 11:D174–D184; doi:10.1080/15459624.2014.933960.
11. Ferrar KJ, Kriesky J, Christen CL, Marshall LP, Malone SL, Sharma RK, et al. 2013. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. International Journal of Occupational and Environmental Health 19:104–112; doi:10.1179/2049396713Y.0000000024.
12. Finkel M, Hays J, Law A. 2013a. The Shale Gas Boom and the Need for Rational Policy. American Journal of Public Health e1–e3; doi:10.2105/AJPH.2013.301285.
13. Finkel ML, Hays J. 2013. The implications of unconventional drilling for natural gas: a global public health concern. Public Health 127:889–893; doi:10.1016/j.puhe.2013.07.005.
14. Finkel ML, Hays J, Law A. 2013b. Modern Natural Gas Development and Harm to Health: The Need for Proactive Public Health Policies. ISRN Public Health; doi:http://dx.doi.org/10.1155/2013/408658.
15. Finkel ML, Law A. 2011. The rush to drill for natural gas: a public health cautionary tale. Am J Public Health 101:784–785; doi:10.2105/AJPH.2010.300089.

16. Goldstein BD. 2014. The importance of public health agency independence: marcellus shale gas drilling in pennsylvania. Am J Public Health 104:e13–15; doi:10.2105/AJPH.2013.301755.
17. Goldstein BD, Kriesky J, Pavliakova B. 2012. Missing from the Table: Role of the Environmental Public Health Community in Governmental Advisory Commissions Related to Marcellus Shale Drilling. Environ Health Perspect 120:483–486; doi:10.1289/ehp.1104594.
18. Hill M. 2014. Shale gas regulation in the UK and health implications of fracking. The Lancet 383:2211–2212; doi:10.1016/S0140-6736(14)60888-6.
19. Kaktins NM. 2011. Drilling the Marcellus shale for natural gas: environmental health issues for nursing. Pa Nurse 66: 4–8; quiz 8–9.
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25. Law A, Hays J, Shonkoff SB, Finkel ML. 2014. Public Health England's draft report on shale gas extraction. BMJ 348:g2728–g2728; doi:10.1136/bmj.g2728.
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28. Mash R, Minnaar J, Mash B. 2014. Health and fracking: Should the medical profession be concerned? S. Afr. Med. J. 104: 332–335.
29. McDermott-Levy BR, Kaktins N, Sattler B. 2013. Fracking, the Environment, and Health. AJN, American Journal of Nursing 113:45–51; doi:10.1097/01.NAJ.0000431272.83277.f4.
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31. McKenzie LM, Guo R, Witter RZ, Savitz DA, Newman LS, Adgate JL. 2014. Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado. Environmental Health Perspectives 122; doi:10.1289/ehp.1306722.
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Washington County, Pennsylvania. Environmental Health Perspectives; doi:10.1289/ehp.1307732.
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41. Shonkoff SB, Hays J, Finkel ML. 2014. Environmental Public Health Dimensions of Shale and Tight Gas Development. Environmental Health Perspectives 122; doi:10.1289/ehp.1307866.
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- *No indication of significant risks or adverse health outcomes (n = 2)*

1. Bunch AG, Perry CS, Abraham L, Wikoff DS, Tachovsky JA, Hixon JG, et al. 2014. Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks. Science of The Total Environment 468–469:832–842; doi:10.1016/j.scitotenv.2013.08.080.
2. Fryzek J, Pastula S, Jiang X, Garabrant DH. 2013. Childhood cancer incidence in pennsylvania counties in relation to living in counties with hydraulic fracturing sites. J. Occup. Environ. Med. 55:796–801; doi:10.1097/JOM.0b013e318289ee02.

Water Quality: Original Research (n = 29)

- *Indication of potential, positive association, or actual incidence of water contamination (n = 21)*

1. Darrah TH, Vengosh A, Jackson RB, Warner NR, Poreda RJ. 2014. Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. PNAS 201322107; doi:10.1073/pnas.1322107111.
2. Davies RJ, Almond S, Ward RS, Jackson RB, Adams C, Worrall F, et al. 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Marine and Petroleum Geology 56:239–254; doi:10.1016/j.marpetgeo.2014.03.001.
3. Ferrar KJ, Michanowicz DR, Christen CL, Mulcahy N, Malone SL, Sharma RK. 2013. Assessment of effluent contaminants from three facilities discharging Marcellus Shale wastewater to surface waters in Pennsylvania. Environ. Sci. Technol. 47:3472–3481; doi:10.1021/es301411q.
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