Hydraulic Fracturing: Potential Impacts to Wetlands

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INTRODUCTION

Unconventional oil and gas extraction using hydraulic fracturing has disrupted traditional energy technologies. Shale formations are a vast global resource (US EIA 2011) facilitating a worldwide transition to gas-centric economies. While hydrocarbon reserves in shale formations exist globally (Figure 1), most of the production of gas from shale currently occurs in North America (Nicot and Scanlon 2012). With over 50,000 new unconventional oil and gas wells being drilled annually since 2000 in central North America alone (Allred et al. 2015), and a likely production growth of 60% in the U.S. (US EIA 2015), it is no surprise that unconventional gas drilling has received much attention in recent years. However, its potential impact on natural resources, particularly water quality and quantity, has also garnered much attention in the media and more recently in the scientific literature. Adding fuel to this controversy is a the recent draft EPA report press release with its headline: *Assessment shows hydraulic fracturing activities have not led to widespread, systemic impacts to drinking water resources and identifies important vulnerabilities to drinking water resources* (US EPA 2015a). Here, we summarize the unconventional oil and gas drilling process, discuss benefits, and describe the environmental concerns potentially affecting wetlands, including both those contained and overlooked in EPA's recent draft report.

Extracting Oil and Natural Gas from Shale. Recent advances in the hydraulic fracturing process combined with the advent of horizontal drilling technology has resulted in the rapid development of unconventional oil and natural gas deposits in the United States. Conventional oil and natural gas extraction involves drilling single, vertical wells into naturally occurring reservoirs of gas or oil, but hydrocarbons in shale deposits are distributed throughout sedimentary rock deposits and are unavailable using conventional drilling techniques. A single vertical well would access only a small amount of either oil or gas trapped in pore spaces of the relatively thin shale layer. To increase the efficiency of resource extraction in shale deposits, two advances in drilling technology have been paired: directional drilling and hydraulic fracturing (Figure 2). Directional drilling allows a well to be sunk to the depth of the shale deposit (often thousands of meters below the surface) and then turned to direct the well horizontally through the shale. The horizontal portion of the well that is in contact with the shale can also be thousands of meters long. This portion of the well is then hydraulically fractured. During hydraulic fracturing, a mixture of water and sand, along with a proprietary mixture of "fracking fluids," are pumped down the well at high pressures (10,000–20,000 psi; Jackson et al. 2014) to fracture the surrounding rock and release hydrocarbons held in micropores and/or adsorbed onto organic matter in shale deposits (Nicot and Scanlon 2012). This natural gas or oil can then travel through the fissures created in the shale to the well. The injected water also returns to the surface with the hydrocarbon resource (discussed in more detail in General Environmental Concerns). Individual wells may be fractured multiple times resulting in the return of both the hydrocarbon resource and wastewater. The paved pads supporting the necessary drilling infrastructure may host multiple wells.

The first large-scale foray in unconventional drilling using horizontal drilling and hydraulic fracturing occurred in the Barnett Shale in Texas (Jackson et al. 2014). There are now more than 15 active shale plays (oil and gas accumulations with similar physical characteristics) in the U.S. (Brantley et al. 2012) with the seven regions accounting for 95% of domestic oil production growth and all domestic natural gas production growth during 2011-13: Bakken, Eagle Ford, Haynesville, Marcellus, Niobrara, Permian, and Utica (Figure 3; US EIA 2015a). Daily natural gas production from these regions in July 2014 was estimated at 1,292 million m^3 (45,646 million ft^3) with Marcellus (36%), Eagle Ford (16%), and Haynesville (15%) as the three biggest producers (US EIA 2015a). The Marcellus region has the highest production in the U.S., with 7,100 active wells in Pennsylvania alone (Amico et al. 2015). Daily oil production nationwide is estimated at 5,486 thousand barrels with the Permian, Eagle Ford, and Bakken regions leading the way (US EIA 2015a). Future energy forecasts suggest increased unconventional natural gas production will almost double by 2040, while unconventional oil production will increase by 36% over the same time frame (US EIA

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2015b). Directional drilling along with hydraulic fracturing (together called "fracking") have significantly increased the natural gas and oil production potential from shale and have made the extraction process economically feasible.

BENEFITS OF HYDRAULIC FRACTURING

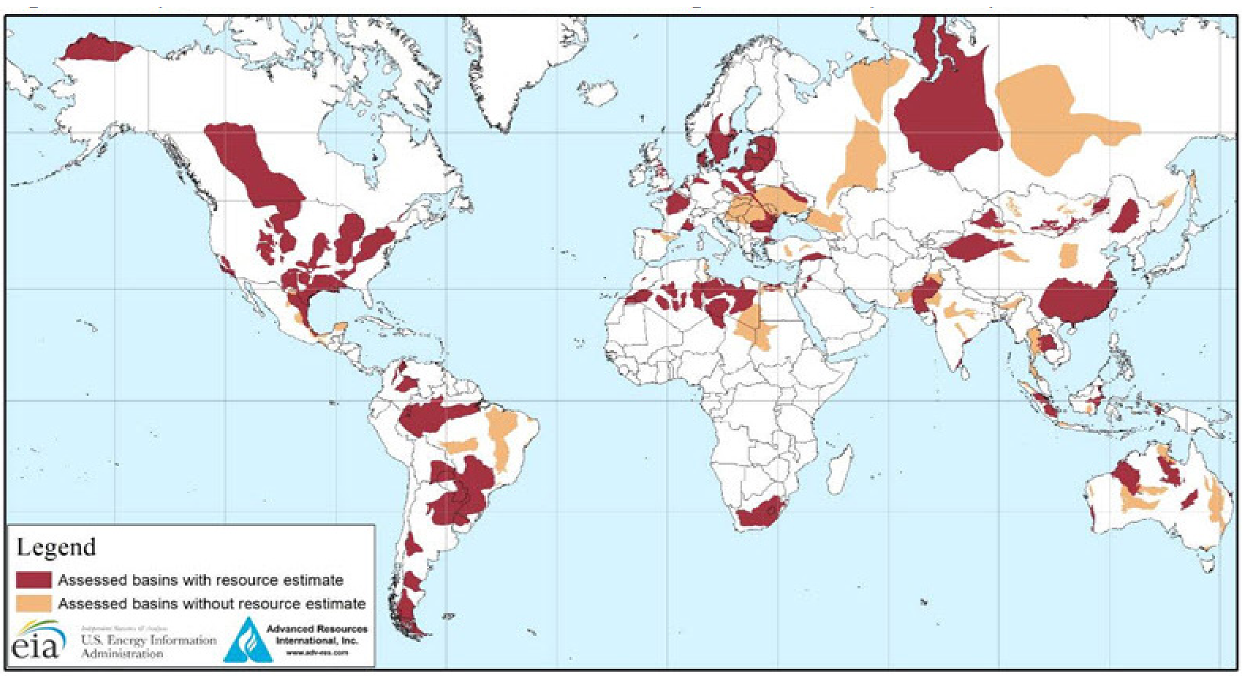
There are a number of benefits to hydraulic fracturing, notwithstanding environmental effects that warrant further investigation. While hydraulic fracturing is used to obtain both oil and gas reserves, much of the benefit is derived from the transition from liquid petroleum to natural gas as a primary energy source. This transition to an abundant energy source (from oil to gas) has led proponents to espouse the benefits of hydraulic fracturing for economic prosperity, energy security, and environmental improvements.

Economic Prosperity. Many of the benefits of hydraulic fracturing are attributed to economic prosperity. The economic value of natural gas in some areas has quadrupled in recent years, a clear indication that the industry has reached a boom status (Weber 2012). The rise of influence of natural gas has led to lower domestic natural gas prices, and the unconventional hydraulic fracturing technology has been behind the reduction (Sovacool 2014*).* Some local areas welcome the industry (Sontag and Gebeloff 2014), while others do not (Sovacool 2014). The industry has brought wealth to some regions; an influx of skilled workers can lead not only to an increase in the local service economy, but can lead to more permanent economic improvements, such as increases in housing prices due to an inelastic supply (Weber 2012).

On the other hand, energy booms are often short-term, and cycles of boom and bust are rarely managed in advance. Economists offer the concept of a "resource curse" where reliance on natural resources is inversely correlated to economic growth, and the relationship has both political and economic underpinnings (Weber 2012). Hydraulic fracturing has allowed large increases in gas production which have led to modest increases in median household income, employment, and salary and wage income, but wage increases are dependent upon local factors such as commute time/distance, existing wage rate, and worker skill set. Economic benefits tied to hydraulic fracturing can also extend beyond the immediate locality of drilling activity in stimulating manufacturing activities that support drilling and other products that rely on inexpensive natural gas (e.g. plastic, agrochemicals, pharmaceuticals; Sovacool 2014). Gas extraction taxes can also be used to support statewide initiatives (Weber 2012).

The resource curse was not evidenced in an analysis of labor markets in the south-central US; however, sources of public revenue and expenditures may not yet be apparent (Weber 2014). Often absent in this calculation are negative externalities, which must be incorporated and assessed to the entity responsible for creating impacts. Of course, proving causality of an individual entity without a baseline is difficult if not impossible; thus, calculations neglect the cost for any negative by-products of the technology. Policies currently in place for the unconventional extraction are more closely aligned with conventional gas policies, but the consequences are more akin to those of non-point source

FIGURE 1.
Global assessed shale oil and gas formations as of May 2013. (Image courtesy US EIA)



Source: United States basins from U.S. Energy Information Administration and United States Geological Survey; other basins from ARI based on data from various published studies.

pollution; hence, appropriate future policy measures might take a different approach than those currently in place (Holahan and Arnold 2013).

Energy Security. At current extraction and consumption rates (including extensive exports), U.S. estimates suggest that hydraulic fracturing provides a lifespan of natural gas at 45 years from the Marcellus play alone (Sovacool 2014) to 65 years nationwide (Howarth et al. 2011). U.S. government projections suggest that oil production from tight oil plays (e.g., shale) will substantially rise over the next decade and thus allow the U.S. to reduce the need for imports (US EIA 2015). The abundance of the resource lessens the source country's dependence on imports, thus reducing the likelihood of conflict over an energy source. It might be an interesting analysis to calculate the resource lifespan if exports slowed, allowing a concomitant delay in production. Presumably, if the hydrocarbon remained in the country of origin for longer term use, energy security would extend to greater timeframes than current estimates.

Environmental. Unlike the combustion of coal and petroleum, use of natural gas does not emit carbon dioxide (CO_2). Thus, natural gas potentially removes CO_2 as a by-product of energy generation, so long as renegade emissions are prevented (Sovacool 2014). Shale gas also has lower emissions of other gases, including sulfur oxide, nitrogen oxide and mercury relative to its fossil fuel counterparts (Sovacool 2014). If completed properly without any leaks, proponents argue that the transition to a gas-based fossil fuel could be a step toward lowered atmospheric greenhouse gases, but renegade methane leaks remain a concerning greenhouse gas emission.

GENERAL ENVIRONMENTAL IMPACTS

Few data-driven studies on the impacts of hydraulic fracturing have been published, and virtually none address wetlands specifically. We review the limited existing scientific literature on environmental impacts of hydraulic fracturing that might affect wetlands and then draw on those impacts to extend the risks to wetlands in the subsequent section. Given the landscape positions of many wetlands (in drainage depressions or at the interface between groundwater and the land surface), they are particularly vulnerable to all impacts to water resources, thus research in water quantity and quality are presented. Wetlands also serve as habitat to wildlife species, of course, so we consider wildlife impacts. We do not include other important effects that are not relatable to wetlands; thus induced seismicity, air quality, and human health are excluded from this report.

FIGURE 2.
The hydraulic fracturing process. (Image courtesy Al Granberg/ProPublica)

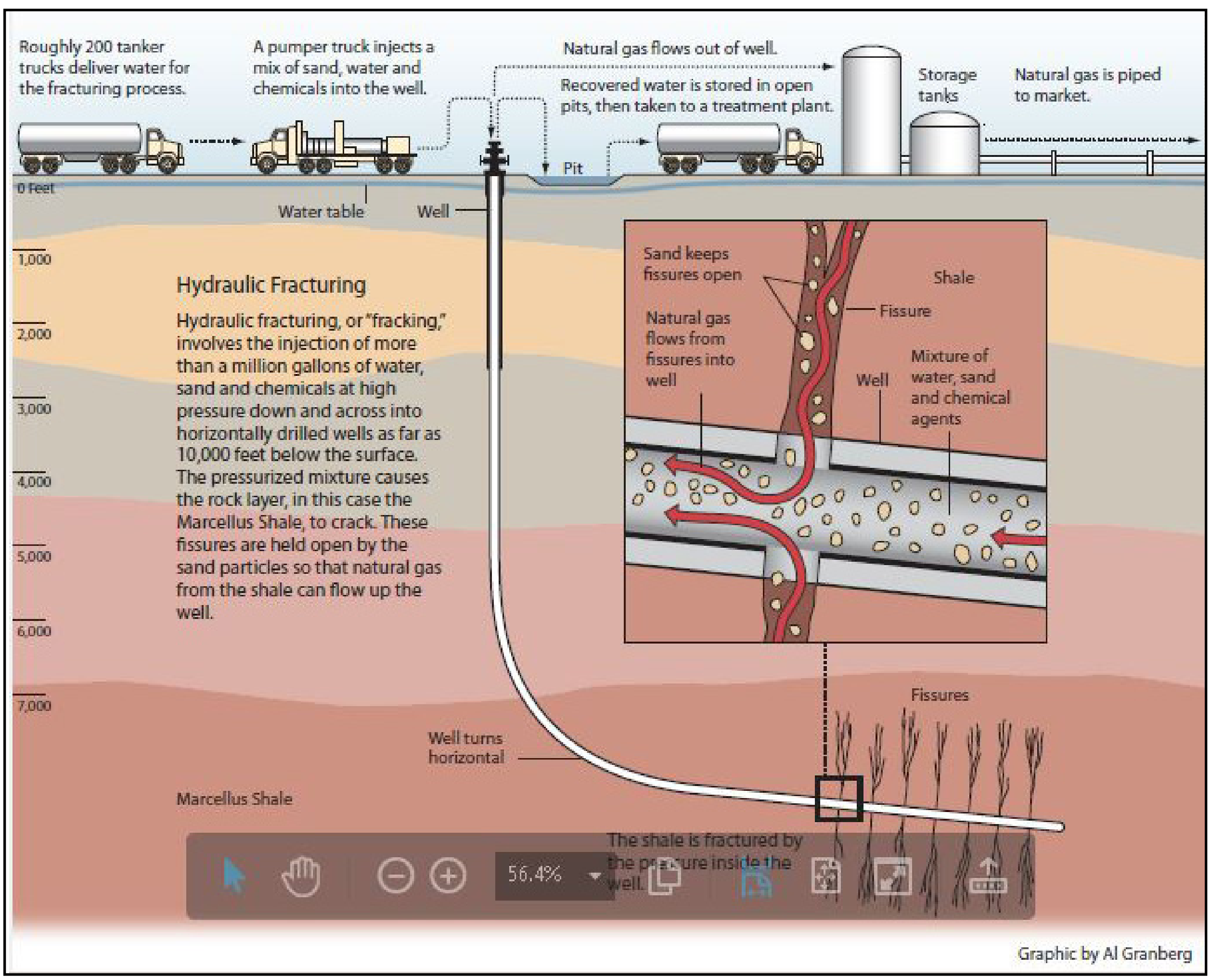


FIGURE 3.
Shale plays in North America as of May 2011. (Image courtesy US EIA)

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011

Water Quantity. Estimates of water volumes used in the hydraulic fracturing process vary from ~8,000 to 80,000 m^3 (2–20 million gallons) per well each time it is fractured (Jackson et al. 2014). An additional 25% of that water volume can be used for other steps in the hydraulic fracturing process (Nicot and Scanlon 2012). Water volumes vary geographically and are a function of the hydrocarbon of interest as well as its relative depth and/or extent below the surface. For example, hydraulic fracturing in the Marcellus region requires about 17,000 m^3 (~4.5 million gallons) of water per well, whereas Texas' Eagle Ford Shale uses up to 50,000 m^3 (~13 million gallons) of water per well (Beauduy 2011). The water used during injection is withdrawn from local surface water or groundwater, though increasingly injection water is being reused. Much of the water injected remains greater than one kilometer underground (e.g., 60-90% of the water in the Marcellus Shale in PA and WV), effectively removed from the surface hydrologic cycle.

Using Pennsylvania as an example, water requirements for the total number of wells since 2007 indicate that 100.7 million – 134 million m^3 (26.6 - 35.4 trillion gallons) of water were removed from the surficial hydrologic cycle. These values likely represent a minimum as they do not take into consideration how many times each individual well has been pressure-injected, or fractured ("fracked"). Although Pennsylvania is generally considered a water-rich state, in 2012 the Susquehanna River Basin Commission temporarily suspended hydraulic fracturing water withdrawal permits in five counties due to low stream levels (NPR 2012). The fact that the region was not experiencing a drought during this time suggests that natural gas operations are creating conflicts with other users under normal conditions. The Susquehanna River Basin currently contributes over 98 million m^3 (26 billion gallons) of water to the Chesapeake Bay daily (Drohan et al. 2012b). Withdrawal is expected to increase to over 113 million m^3 (30 million gallons) needed when peak gas production is reached (Drohan et al. 2012b). Given the proposed expansion and growth of drilling in PA, conflicts between natural gas companies and other water users are likely to intensify.

Water Contamination. The injection fluid used for hydraulic fracturing is a mixture of solids and chemicals added prior to injection, which becomes further mixed with brine (ancient seawater) associated with shale deposits during fracturing. The injection fluid is water (generally > 90%), a proppant (used to keep the fissures open; usually sand), and chemicals to adjust the properties of the injection fluid. The volume of the added chemicals is generally <2% of the injection fluid volume, though with the large volumes of water required for hydraulic fracturing the total volume of chemicals used would typically be in the thousands of gallons per well. There have been more than 1000 unique chemicals used in hydraulic fracturing operations nationally, with typically <30 unique chemicals per well; the specific composition of injection fluid varies widely. Voluntary self-reporting of hydraulic fracturing fluids have shown they can include acids (*e.g.,* hydrochloric acid), friction reducers, and corrosion inhibitors designed to protect pipe integrity (e.g., ammonium persulfate, ethylene glycol, and isopropanol), and anti-scalents and biocides to prevent the build-up of bacteria and chemical precipitation in pipes and pores (e.g., acrylic and carboxylic polymers, and glutaraldehyde (see www.fracfocus.org for more complete synopsis of fracturing fluids as well as examples of specific compounds). The voluntary nature of the reporting as well as the lack of reporting of chemicals deemed propriety has led to complaints regarding the transparency of the true composition of injection fluid.

Once injected during the hydraulic fracturing process, the injection fluid comes into contact with the shale rock and mixes with brine confined within the shale. As the acidic injection fluid interacts with the shale and brine, the resulting fluid can become enriched with salts (e.g., sodium, chloride, and sulfate; Haluszczak et al. 2013), heavy metals (notably arsenic and selenium; Balaba et al. 2012), and radionuclides (radium; Warner et al. 2012). The returned water, or flowback water, from hydraulic fracturing activities, therefore, is a variable mixture of high total dissolved solids (TDS), organic compounds, major ions, trace metals, and radionuclides, which depends on the chemicals added to the injection fluid, the chemistry of the shale deposit and brine, and the interactions between the two sources during the fracturing process.

Once a well has been fractured, some portion of the injection fluid returns to the surface, along with the produced gas (largely methane) and/or oil. Eventually, ancient, naturally occurring water previously held deep in the Earth ("produced water") also makes its way to the surface. This combined flowback and produced water, if not properly collected, stored, and treated, can contaminate aquatic resources. Returned water is often temporarily stored in surficial lined pits designed to let evaporation reduce the overall quantity for off-site disposal. Increased storage time, however, runs the risk that improperly constructed pits may leak or that tears in pit linings could contribute to localized groundwater impacts. This avenue of delivery along with leaks from poorly constructed and/or maintained gas well casings has also been tentatively linked to negative impacts in private drinking water wells. Impacts associated with individual spills and well disasters have been reported, but research has not identified wide-scale degradation to surface or ground water resources, in part because of the unpredictable timing of such events.

Wells often are drilled through shallow aquifers to reach shale deposits thousands of meters below the surface. At shallow depths, multiple layers of well casing with cement between each layer are intended to isolate the injection fluid, flowback, and produced gas or oil from the surrounding lithology and groundwater. However, faulty well construction, inadequate layers of casing or cement, or failure of the well casing can lead to the leakage of fluids and gases from the well into shallow groundwater resources. Migration of fluid or gas from the shale production zone up along the outside of the well or through existing or newly created fractures into shallower groundwater or surface water also is a concern. These possible routes of contamination are controversial, remain relatively undocumented, and are the focus of active research (Vengosh et al. 2014).

Certain vulnerabilities to groundwater do exist and have been reported in the scientific literature. Several published studies have used a variety of tracers to confirm the presence of fugitive or stray methane gas emissions in shallow aquifers. Using a dataset of 60 drinking water wells in Pennsylvania and New York, for example, Osborn et al. (2011) identified methane concentrations approximately 17 times higher in active extraction areas. The authors used stable carbon isotopes of methane as well as ratios of methane to higher-chain hydrocarbons to suggest input from deep thermogenic methane. Additional studies have used chemical fingerprints of gas (e.g., ethane and propane not found in biogenic methanogenesis) as well as select noble gas concentrations to confirm shallow aquifer contamination was occurring as the result of stray gas migration of deep thermogenic methane (Jackson et al. 2013; Darrah et al. 2014). Interestingly, evaluation of major elemental concentrations (Br^-, Cl^-, Na^+, Ba^{+2}, Sr^{+2}, and Li^+) and isotopic ratios ($^{87}Sr/^{86}Sr$, $^2H/H$, $^{18}O/^{16}O$, and $^{228}Ra/^{226}Ra$) in these same wells revealed no distinctive input of Marcellus brine (Warner et al. 2012). However, a more recent study conducted in Bradford County, PA confirmed the presence of the hydraulic fracturing chemical 2-n-Butoxyethanol in a drinking water well located over a kilometer from a nearby hydraulic fracturing well (Llewellyn et al. 2015). Additional studies from Wyoming also confirm the presence of organic compounds, such as benzene, toluene, ethylbenzene, and xylenes, and elevated concentrations of TDS, methane, and ethane in monitoring wells located in regions of active hydraulic fracturing that have experienced known spills (DiGiulio et al. 2011; Wright et al. 2012).

Surface water contamination from hydraulic fracturing activities also has been documented in the literature. Studies in the Marcellus region have identified the presence of significantly higher concentrations of Cl^- and Br^- in stream water (Olmstead et al. 2013; Warner et al. 2013) as well as ^{226}Ra levels downstream of industrial wastewater facilities that treat hydraulic fracturing wastewater (Warner et al. 2013). It follows that landscape disturbance associated with well pad construction will also exhibit an impact on stream water quality just as any other industrial disturbance or construction activity. An initial survey of watersheds in the Fayetteville shale by Entreken et al. (2011) found a link between well density and stream water turbidity values during high flow periods. Interestingly, this study was performed early during the hydraulic fracturing boom and does not take into consideration disturbances associated with the construction of pipelines or compressor stations.

While evidence of surface and groundwater contamination in the scientific literature is primarily limited to these aforementioned studies, it is safe to conclude that the number of documented releases and/or violations, particularly those associated with cementing, casing, and well construction, have likely influenced water quality in some capacity.

Wildlife. Flora and fauna in the proximity of a surface or groundwater spill risk exposure to contamination. Species susceptible to chloride, heavy metals and sedimentation that have been found in some local studies are at particular risk. Vegetation sprayed with hydraulic fracturing fluid in an experimental forest displayed severe damage and mortality within 10 days of application; soil sodium and chloride increased 50 fold and became more acidic with over 50% tree mortality after two years (Adams 2011). Fish and possibly aquatic invertebrates in southeastern Kentucky were adversely affected by unauthorized disposal of hydraulic fracturing fluids (Papoulias and Velasco 2013). Certain species may also have aversion to light and sound affiliated with unconventional drilling installations during active periods.

More widespread effects occur with the conversion of forested or other undeveloped land to industry, and the fragmentation that results when constructing well pads, pipeline corridors and compressor stations. An assessment of the central U.S. estimates that approximately 3 million ha were converted to drilling installations between 2000-2012 (Allred et al. 2015). In the Marcellus Shale, one estimate suggests that each installation (including well pad, access road, storage area, compressor station, and collector pipeline) affected 12-15 ha and led to 80% of land being fragmented to the point of harming interior species that require a minimum of 100 m of connected forest (Johnson 2010; Kiviat 2013). Drohan and colleagues (2012a) predicted approximately 650 km of roads would be installed based on permitted activity in the summer of 2011.

Fragmentation (i.e., the breaking up of contiguous blocks of undisturbed habitat) has been shown to have many adverse effects on wildlife, including the loss of core/interior habitat (thus changing patch size and connectedness to other patches), and changes in light, moisture, and temperature (Harper et al. 2005). Fragmentation disrupts pollination, dispersal, herbivory and predation and may lead to greater invasion of nonnative plants, introduction of songbird nest predators, severed migratory pathways, and altered wildlife behavior and mortality (Kiviat 2013; Allred et al. 2015). The warming and drying associated with fragmentation also is suspected in the decline of certain amphibians (Brand et al. 2014). Preliminary results of research in Pennsylvania's Marcellus Shale indicate that specialist avian species are more affected by the installations than are generalists; synanthropic species (those associated with humans) are highest nearest installations; whereas, interior forest species decline less than 150 m from the pads (Brittingham et al. 2014a). As might be expected, forest interior species decreased in abundance with increasing well pad density (Thomas et al. 2014).

Globally, shale gas resources are extensive and often intersect with areas of high biodiversity, such as northern South America and the western Pacific Ocean (Butt et al. 2013). This combination points to the importance of protecting biodiversity when gas development begins in earnest outside of North America. Regional plans for drilling might consider consolidating infrastructure and balancing what will likely be a wider footprint with fragmentation in each specific area. To date, restoration from abandoned drilled areas in central North America has not replaced what has been destroyed (Allred et al. 2015). Restoration of sites after drilling is complete will be critical in all areas subjected to unconventional drilling, and preparations should be required at the time of installation to ensure site-specific coarse woody debris and migration corridors are in place (Northrup and Wittemyer 2013). Vegetation that supports targeted fauna should be seeded/planted to kick start the return to baseline function.

Cumulative Impacts. Landscapes can be resilient, but the impacts of unconventional drilling coupled with climate change and other land use changes may lead to unexpected consequences. The scale of environmental degradation suggests that the loss of many ecosystem services is being overlooked. This may be due, in part, because most studies focus on smaller areas (Allred et al. 2015). In Pennsylvania alone, unconventional drilling permits issued by June 2011 could lead to development of 1180-1966 ha, degrading 45-62% in agricultural lands and 38-54% in forested lands (Drohan et al. 2012). Evans and Kiesecker (2014) predicted energy developments would impact upwards of 440,000 ha of forest and over half a million hectares of impervious surface in modeled build-out scenarios within the Marcellus Shale. It follows that this large-scale alteration of the landscape will alter the local hydrology in these settings similar to what is experienced via stormwater runoff in more developed settings.

Many processes within and among ecosystems – whether producer-based ("green") or detritus-based ("brown", like many wetlands) trophic webs – are regulated by the amount of biomass produced as a result of net primary production (NPP). Allred and colleagues (2015) found that the estimated loss of NPP to hydraulic fracturing in 2000-2012 from rangeland and cropland is ~4.5 Tg of C (10 Tg dry biomass) across Central North America

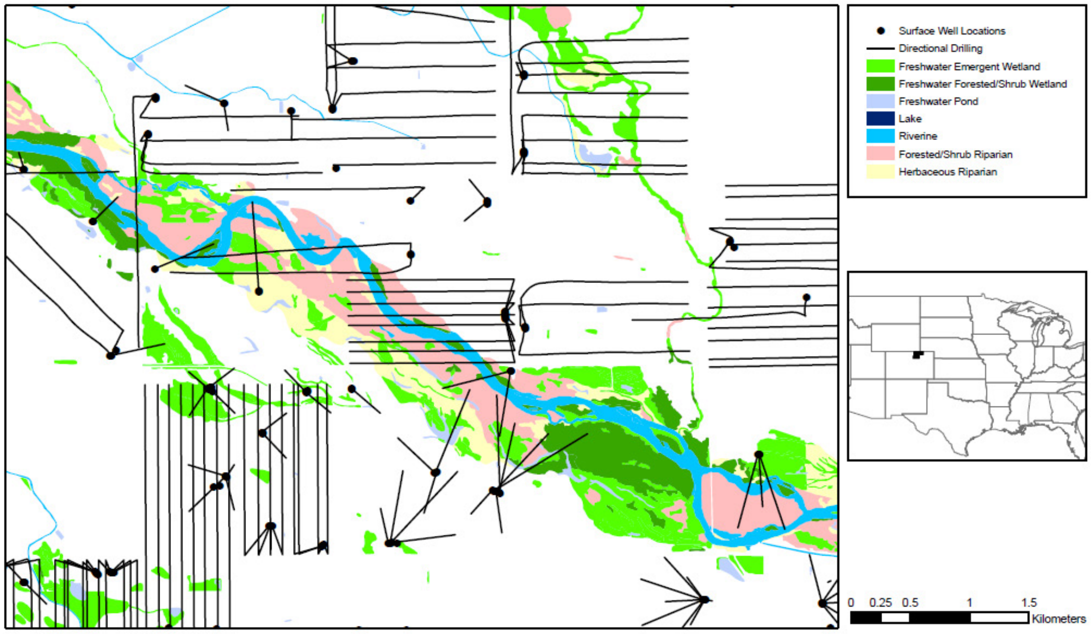


FIGURE 4.
Portion of the South Platte River in Weld County, CO (indicated on inset map) showing wetlands (from National Wetlands Inventory) and oil and gas wells with subsurface horizontal directional drilling lines indicated (Colorado Oil and Gas Commission; data for active wells and wells in production, drilling, or injection stage as of 9 June 2015).

Note that only wells with directional drilling were included here, as presumably these sections were hydraulically fractured (specific data on hydraulic fracturing activity was not available), and that a single surface well location may host numerous subsurface directional wellbores. Many other vertical-only wells (some of which may have been fractured) are not included here.

(U.S. and Canada) alone. The lost rangeland is the equivalent forage that would feed 5 million animals for a month; the cropland loss is equivalent to 120.2 million bushels of wheat (Allred et al. 2015). The rapid installation of drilling infrastructure, therefore, has potential ramifications throughout the food web, suggesting the importance of building regional planning and monitoring networks. The conversion of agriculture to unconventional drilling installations (Drohan et al. 2012a; Allred et al. 2015) also has the potential to place important land uses in competition with one another as the energy industry approaches maximum build-out in future years.

Cumulative impacts are difficult to assess: scales can be broad, baseline data may be difficult to obtain, and causality is challenging to establish. As a result, few data-driven, published studies exist in the literature. As Allred and colleagues (2015) point out, a perfect storm may be brewing between agriculture, environmental conservation, and energy demands on the remaining undeveloped landscape. The last time the U.S. saw conflicts of this scale led to the Dust Bowl (1930s). With an abundance of data on related activities currently available and the lessons learned from history, we have an opportunity to act now to prevent such catastrophic events.

CONCERNS FOR WETLAND IMPACTS

Concerns about drilling and hydraulic fracturing activities have focused largely on the human health consequences of water and air pollution, though the impacts of changes in water quality and quantity and land-use associated with natural gas and oil extraction on ecosystems are receiving increasing attention. Here, we outline the threats that hydraulic fracturing might pose to wetland systems.

Land Use Change. The installation of new unconventional wells and related infrastructure each year drives substantial change in land use. Transformation of wetlands for other uses has long been the leading cause of wetland loss (Dahl 1990). Before new gas or oil wells are drilled and hydraulically fractured, land is cleared for the construction of a well-pad at the site of the drilling. In addition, pipelines are installed, new roads are built (in most cases), and supporting infrastructure such as natural gas compression stations are erected. While proportionally little of the land used for hydrocarbon extraction activities has directly impacted wetlands (<1% in North America; Allred et al. 2014), wetlands occupy a relatively small footprint on the landscape and even that small presence makes a large contribution to ecosystem health. It is likely that the most common wetland type impacted is the important headwater forested wetland. In Pennsylvania approximately one quarter of all well pads occur in core forest areas where many headwater streams are located (Drohan et al. 2012a).

In addition to direct loss of wetlands from land use change, the process of constructing well-pads, roads, and pipelines may indirectly impact wetlands through an increased area of impervious surfaces (Allred et al. 2014) and the mobilization of sediments and other materials (e.g., Entrekin et al. 2011; Vengosh et al. 2014). These activities may lead to deterioration in water quality (see *Water Quality*, following section), delivery of sediments and pollutants to depositional wetland environments, and changes in hydrology with increased impervious surfaces (along with water extraction; see *Water Usage*, following). The impacts of land use change associated with gas and oil drilling on wetlands remains unclear.

Water Usage. Vengosh and others (2014) estimated that approximately 300 million m^3 (>79 trillion gallons) of water has been used for hydraulic fracturing over the last decade, which represents about 1% of the water lost from evaporation during thermoelectric generation. On a national scale, then, hydraulic fracturing does not substantially alter water usage. Water withdrawals may have greater influence on water resources at the local level, however, that may impact wetland ecosystems. Several of the oil and gas plays in the Central and Western U.S. (for example the Niobrara, Hilliard-Baxter-Mancos, and Mancos plays in CO, NV, WY, and UT, the Barnett and Eagle-Ford plays in TX, and the Monterey play in CA) are situated beneath relatively arid regions. Freyman and Salmon (2013) estimate that about half of the shale gas and oil wells in the nation have been developed in areas with high to extremely high baseline water stress. Surface water or groundwater withdrawals for hydraulic fracturing in these areas may compound agricultural and municipal withdrawals further exacerbating water stress, potentially leading to water shortages for wetland habitats. For example, much of northeast Colorado positioned over the Niobrara shale play is classified as high or extremely high water stress (Freyman and Salmon 2013; Freyman 2014). Directional drilling and hydraulic fracturing activity is rapidly expanding in this a region (Figure 4). This is also a region with abundant freshwater wetland ecosystems (Figure 4). Much of the South Platte River is bounded by extensive riparian meadows and woodlands, and there are wet meadows, freshwater marshes, and submerged aquatic wetland ecosystems found in this region. Many wetlands in this area have been altered by development and agricultural activities, and water availability is a concern in this relatively arid region. Irrigation for agricultural use in the South Platte River basin exerts substantial pressure on the region's water resources. Water withdrawals for hydraulic fracturing activity may further exacerbate depletion of local water resources, creating water stress for wetland ecosystems in the region. The impact of water withdrawals on wetland ecosystems requires further attention.

TABLE 1.
Potential sources of water contamination from unconventional drilling

Standard Operations
On-site spills of chemicals used for injection, and/or spills of produced water
Failed well casing allowing leakage to water table or surface waters
Migration from production zone to water table or surface waters
Improper storage and/or treatment of flowback/produced water
Less Common Scenarios
Well explosions [*examples from Sontag and Gebeloff (2014)*] • North Dakota (2006): 1 environmental incident for every 11 wells • North Dakota (2013): 1 environmental incident for every 6 wells • Well blow outs often withheld from public (e.g. Skurupey in North Dakota)
Incidents during transport • Transmission pipelines leaks • Compressor stations explosions (e.g. Appomattox, VA) • Ports • Nearshore - ships awaiting port entry to load/unload because ports are over capacity or awaiting more favorable market prices • Greatest concern where hydraulic fracturing collects both oil and gas

Water Quality. Hydraulic fracturing for gas and oil carries the potential to contaminate shallow groundwater aquifers and surface water resources at several steps in the process that has the potential to impact wetland ecosystems (Table 1). Since large quantities of the chemicals used to create the injection fluid are transported, stored, and mixed during hydraulic fracturing activities, there is a risk of spillage and/or leakage during each of these steps. In their recent draft assessment, the U.S. EPA (2015b) found that between 0.5 and 12% of wells had reported spills/leaks, yet this is likely underreported, and the volume of unplanned releases are generally not known.

Concerns about pollution from hydraulic fracturing have understandably been focused largely on surface water quality and human health (Olmstead et al. 2013; Vengosh et al. 2014), and, to our knowledge, there has been no research on wetland-specific response to changes in water quality associated with drilling. Wetland ecosystems are likely resilient to low concentrations of many of the chemicals that might be released into surface waters or shallow groundwater, except in the case of acute events. We suggest that the largest widespread concern specifically for wetlands – outside of individual spills – is the potential for an increase in dissolved salts (mainly Cl^-) that might accompany any contamination of water resources. The shale brine contains very high concentrations of salts, and chloride is often added to drilling fluid in the form of hydrochloric acid (US EPA 2015b). Van der Burg and Tangen (2015) identified chloride contamination in many wetlands throughout the Prairie Pothole Region of the U.S. likely associated with unconventional gas drilling. Drilling and hydraulic fracturing activities may, therefore, further exacerbate the general salinization of freshwater systems nationally (Kaushal et al. 2005). Increasing salinity in freshwater wetlands may adversely impact plant growth and alter ecosystem function (Neubauer 2013).

Challenges. The challenges facing quantifying impacts of hydraulic fracturing on wetlands hinge on the many unknowns, which may remain unstudied for some time because of the controversial nature of the topic and/or lack of funding sources. Until baseline data can be obtained, attributing impacts to hydraulic fracturing will remain difficult. Requiring baseline data for drilling on public lands would be a responsible strategy for the publicly held common good, but it would not be adequate as a sole measure since most hydraulic fracturing occurs on private lands (e.g., in the U.S. Great Plains as much as 90% occurs on private lands; Allred et al. 2015). Additionally, a lack of transparency regarding the chemical composition of the injected fluids has impeded the targeted testing for impacts in areas where drilling is already underway. Furthermore, a lack of regulatory inspections in areas of active drilling, suspected under-reporting of known releases, and lack of stream and groundwater monitoring networks in areas of active drilling has not allowed for a full quantification of water quality impacts. Finally, given the relatively new arrival of this technology, we simply do not yet have a handle on the failure rate of well integrity over time.

RECOMMENDATIONS FOR FUTURE INVESTIGATION

The position of wetlands in the landscape suggests that impacts to water resources (both quantity and quality) will be magnified in these valuable and vulnerable systems. Any data-driven research would be a significant contribution to the current level of understanding. Until a systematic monitoring program is in place, there is no way to truly know the impacts of fresh water withdrawals from these systems or the probability of well leaks. It is possible that required routine installation of groundwater monitoring systems analogous to that instituted for underground storage tanks in the mid-1980s would allow for the earlier detection of leaks. In light of the concerns presented herein, we recommend the following research priorities targeting wetlands.

- Determine water budgets in impacted watersheds, especially in high water stress areas to ascertain impacts that water withdrawal may have on aquatic and more particularly wetland resources.
- Create an integrated monitoring system within each shale play to capture long-term responses of targeted contaminants (e.g., salts, metals, and organics) both at individual wells and downstream.
  - Prioritize monitoring in watersheds with spills to see if impacts attenuate, especially organics and metals.
  - Determine the transport and potential accumulation of appropriate contaminants through the food web.
- Discriminate the role of water and/or sediments to wetland long-term survival in heavily impacted watersheds, especially during initial sediment flux during construction and during high runoff events.
- Institute regional siting planning to consolidate infrastructure, thus avoiding wetlands and minimizing fragmentation.
- Design effective restoration and monitoring to ensure sites are returned to functioning areas reaching targeted ecosystem services and species. ■

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