Rapid expansion of natural gas development poses a threat to surface waters

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Extraction of natural gas from hard-to-reach reservoirs has expanded around the world and poses multiple environmental threats to surface waters. Improved drilling and extraction technology used to access low permeability natural gas requires millions of liters of water and a suite of chemicals that may be toxic to aquatic biota. There is growing concern among the scientific community and the general public that rapid and extensive natural gas development in the US could lead to degradation of natural resources. Gas wells are often close to surface waters that could be impacted by elevated sediment runoff from pipelines and roads, alteration of streamflow as a result of water extraction, and contamination from introduced chemicals or the resulting wastewater. However, the data required to fully understand these potential threats are currently lacking. Scientists therefore need to study the changes in ecosystem structure and function caused by natural gas extraction and to use such data to inform sound environmental policy.

Natural gas drilling has dramatically expanded with advances in extraction technology and the need for cleaner burning fuels that will help meet global energy demands. Natural gas is considered a "bridge fuel" to renewable energy resources because its combustion releases fewer contaminants (eg carbon dioxide $[CO_2]$, nitrogen oxide $[NO_x]$, sulfur oxide $[SO_x]$) than compared with that of coal or petroleum. Horizontal drilling and hydraulic fracturing ("hydrofracking" or "fracking") now allow the extraction of vast shale gas reserves previously considered inaccessible or unprofitable. Shale gas production in the US is expected to increase threefold and will account for nearly half of all natural gas produced by 2035 (EIA 2011). This widespread proliferation of new gas wells and the use of modern drilling and extraction methods have now been identified as a global conservation issue (Sutherland *et al.* 2010). Here, we describe the threats to surface waters associated with increased natural gas development in shale basins and highlight opportunities for research to address these threats.

■ Horizontal drilling and hydraulic fracturing

Gas-well drilling has historically used a single vertical well to access gas trapped in permeable rock formations (eg sandstone) where gas flows freely through pore spaces to the wellbore. Unlike these conventional sources, unconventional gas reservoirs are low permeability formations, such as coal beds, dense sands, and shale, that require fracturing and propping (addition of sand or other granular material suspended in the fracturing fluid to keep fractures open) before gas can travel freely to the wellbore. Hydrofracking uses high-pressure fracturing fluids, consisting of large volumes of water and numerous chemical additives, to create fractures, while added propping agents, such as sand, allow the gas to flow. Although hydrofracking was first used in the 1940s, the practice was not widely applied until the 1990s, when natural gas prices increased and advances in horizontal drilling made the technique more productive. Horizontal drilling increases the volume of rock a single well can access, thereby reducing the total number of wells required at the surface. The horizontal leg of a gas well is fractured in discrete lengths of 91–152 m, allowing up to 15 separate hydrofrack "events" along one horizontal well (Kargbo *et al.* 2010). Fracturing depth depends on target rock formations but varies from 150 m to more than 4000 m for the major shale formations in the US (US DOE 2009).

■ Extent of resources

The US currently has 72 trillion cubic meters (tcm) of potentially accessible natural gas – enough to last 110 years, based on 2009 rates of consumption (EIA 2011).

In a nutshell:

- The construction of pipelines and roads coupled with the extraction of natural gas from shale basins may pose environmental threats
- Streams and rivers near newly drilled natural gas wells are vulnerable to sediment runoff, reduced streamflow, and possible contamination from introduced chemicals and the resulting wastewater
- Federal and state environmental regulations may not prevent or mitigate damaging effects to surface waters
- Scientific studies are needed to understand the possible environmental effects caused by activities associated with natural gas extraction

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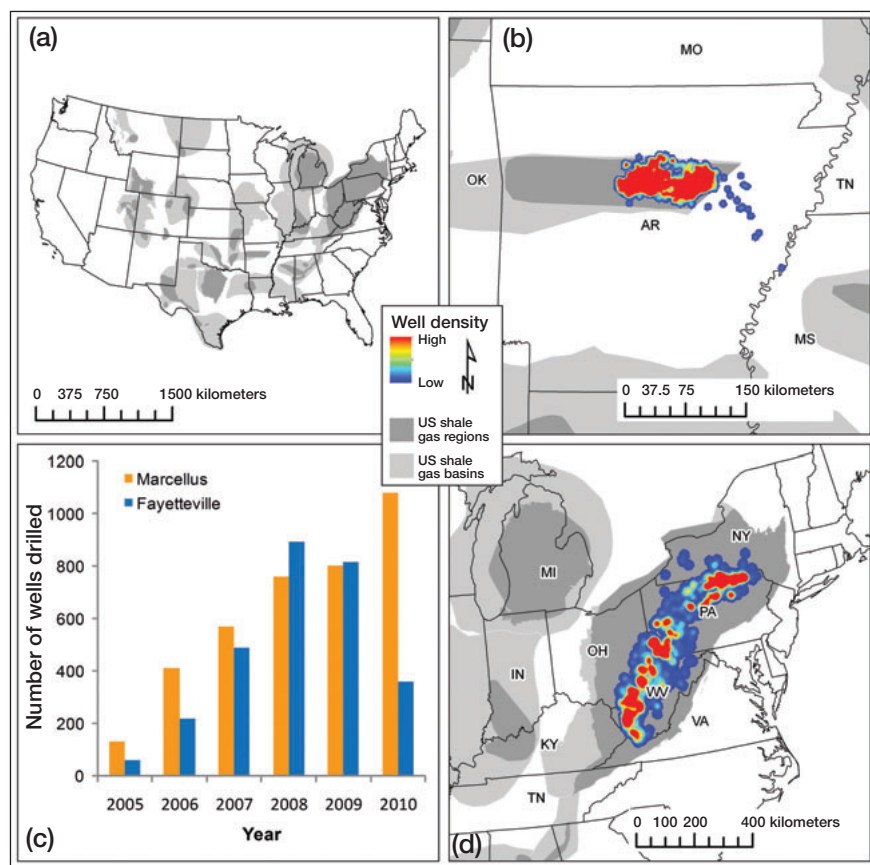
Figure 1. *(a) National map of all recognized potential areas for unconventional natural gas exploration in the contiguous US; (b) density of wells in the Fayetteville unconventional natural gas basins; (c) number of gas wells installed in the Fayetteville and Marcellus basins from 2005 to 2010; and (d) density of wells in the Marcellus shale basins. We calculated densities using the kernel density tool in ArcMap 9.3.1.*

water (eg brines). However, the use of hydraulic fracturing poses additional environmental threats due to water withdrawals and contamination from fracking-fluid chemicals. Extraction of gas from shale formations may also produce considerably more methane (CH_4) than conventional wells and could have a larger greenhouse-gas footprint than other fossil-fuel development (Howarth *et al.* 2011). Furthermore, gas wells are often located adjacent to rivers and streams and may occur at high densities in productive shale basins, resulting in cumulative impacts within watersheds. Environmental and human health concerns associated with hydrofracking have stirred much debate, and the practice has received extensive attention from the media (Urbina 2011) and from researchers (US EPA 2004; Kargbo *et al.* 2010; Osborn *et al.* 2011; US EPA 2011; Colborn *et al.* in press). Research that addresses concerns regarding increased drilling and hydrofracking in shale basins has primarily focused on contaminants that threaten drinking water and groundwater, whereas data collection to address concerns associated with surface water and terrestrial ecosystems has largely been overlooked.

Our goal here is to provide background information on shale development in the US that may inform future ecological studies that assess the potential for environmental impacts. We use data from the Fayetteville and Marcellus shale formations to demonstrate the recent accelerated drilling activity, well proximity to streams, and well density relationships with stream turbidity. We also review other potential threats to aquatic freshwater ecosystems as a result of increased natural gas development.

■ Focus areas

The Fayetteville and Marcellus shale basins are among the most productive in the US. The Fayetteville shale basin underlies more than 23 000 km² of Arkansas and eastern Oklahoma, at a depth of 300–2000 m (Figure 1a). The number of gas wells sited in this area has increased nearly 50-fold, from 60 to 2834 wells since 2005, in a concentrated area of north-central Arkansas (Figure 1, b and c). The Marcellus shale basin spans 240 000 km² at a depth of 1200–2500 m and underlies six states in the upper Mid-Atlantic, including much of the Appalachian region (Figure 1d). Estimates indicate natural gas reserves in the Marcellus to be 14 tcm, or 59% of the total esti-

Approximately 23 tcm of that gas is found in unconventional (ie low permeability) gas reservoirs; development of such reservoirs has increased by 65% since 1998 (US DOE 2009). There are 29 known shale basins spanning 20 states, which are expected to contribute 45% of the total US gas produced by 2035 (EIA 2011; Figure 1a). Furthermore, the US gas supply represents only a fraction of the total global estimate of potentially accessible natural gas (~459 tcm) and, outside of North America, only 11% has so far been recovered (MIT 2010). Development of potentially accessible natural gas is expected to increase with rising global demand and the transfer of drilling technologies overseas.

■ Threats to surface waters

The rapid expansion in natural gas development threatens surface-water quality at multiple points, creating a need to assess and understand the overall costs and benefits of extracting this resource from shale reservoirs. Gas-well development of any type creates surface disturbances as a result of land clearing, infrastructure development, and release of contaminants produced from deep ground-

mated unconventional reserves in the US (US DOE 2009). As of summer 2010, the Marcellus had 3758 natural gas wells, with projections of up to 60 000 wells being constructed in the region over the next 30 years (Johnson 2011). The Marcellus formation also underlies sensitive watersheds, such as the threatened upper Delaware River, a designated wild and scenic river that supplies drinking water to >15 million people (DRBC 2008). The rapid development of gas wells in relatively concentrated areas may increase the likelihood of ecological impacts on surrounding forests and streams.

### ◼ Proximity of gas-well development to water resources

We initially assessed the proximity of active gas wells to water resources using state well-location data and the National Hydrography Dataset (NHD) flowlines (ie streams and rivers mapped from 1:24 000 Digital Line Graph hydrography data). Spatial analysis indicated that, for both the Fayetteville and Marcellus shale formations, gas wells were sited, on average, 300 m from streams, yet several hundred wells were located within 100 m of stream channels (Table 1). Gas wells were located, on average, 15 km from public surface-water drinking supplies, and 37 km and 123 km from public well water supplies in the Marcellus and Fayetteville shale reservoirs,

respectively (Table 1). Although wells are generally constructed far from public drinking-water sources, there is potential for wastewater to travel long distances, given that many of the components of produced waters (ie a mixture of fracking fluids and natural geologic formation water flowing back out of the well), such as brines, will not settle out or be assimilated into biomass. Furthermore, the NHD underestimates the density of headwater stream channels (Heine *et al.* 2004), so our proximity measures probably underestimate the threat to streams. We therefore used geographic information system (GIS) tools to generate detailed drainage-area networks in portions of the Fayetteville and Marcellus shale reservoirs where gas wells occur at high densities. The terrain processing tools in ArcHydro Tools 9 version 1.3 (an ArcGIS extension) were used to generate drainage area lines from 10-m digital elevation models (http://seamless.usgs.gov/ned13.php) in a subset of drainage areas in each shale basin. A stream threshold of 500 (50 000 m^2) was used to define stream channels in the model. Gas-well proximity was analyzed again with a subset of modeled stream drainage areas and the same subset of NHD flowlines for comparison (Figure 2; Table 2). Active gas wells were an average of 130 m and 153 m from modeled drainage areas, as compared with 230 m and 252 m from NHD flowlines, in the Fayetteville and Marcellus shale reservoirs, respectively. Over 80% of the

Table 1. Number of unconventional gas wells drilled each year since 2005 for Arkansas, New York, Ohio, Pennsylvania, and West Virginia

	State	Total wells	Total operators	Distance to NHD flowlines (mean ± SD, range, m)	Total # (percent) of wells within			Distance to	
					100 m of NHD flowlines	200 m of NHD flowlines	300 m of NHD flowlines	public water wells (mean ± SD, range, km)	public drinking-water intakes (mean ± SD, range, km)
Marcellus	PA	2091[*]	59	319 ± 171 (8–1172)	74 (4)	577 (28)	1141 (55)	25.83 ± 17.93 (0.32–79.60)	14.83 ± 10.06 (0.60–50.23)
	WV	1599[†]	86	214 ± 143 (1–850)	409 (26)	798 (50)	1198 (75)	52.32 ± 32.81 (0.55–125.42)	11.16 ± 5.36 (0.53–33.32)
	OH	42[‡]	12	230 ± 153 (46–691)	8 (19)	23 (55)	33 (79)	71.85 ± 28.29 (26.46–138.17)	14.15 ± 8.38 (1.54–29.87)
	NY	26[§]	9	247 ± 182 (27–631)	9 (35)	12 (46)	14 (54)	10.47 ± 7.11 (2.58–34.19)	16.59 ± 9.06 (4.58–35.63)
	All four states combined	3758		273 ± 168 (1–1172)	500 (13)	1410 (38)	2386 (64)	37.51 ± 28.88 (0.32–138.17)	13.27 ± 8.55 (0.53–50.23)
Fayetteville	AR	2834[¶]	21	353 ± 241 (7–1642)	269 (10)	900 (32)	1434 (51)	123.67 ± 11.12 (78.94–156.12)	15.15 ± 7.49 (0.66–133.43)

Notes: [*]PA: Pennsylvania Department of Environmental Protection Bureau of Oil and Gas (records available through 30 Sep 2010), www.dep.state.pa.us/dep/deputate/minres/oilgas/reports.htm; [†]WV: West Virginia Geological and Economic Survey (records available through early Sep 2010), www.wvges.wvnet.edu/www/datastat/devshales.htm; [‡]OH: Ohio Department of Natural Resources Division of Mineral Resources Management (records available through 30 Sep 2010), www.dnr.state.oh.us/mineral/database/tabid/17730/Default.aspx; [§]NY: New York State of Environmental Conservation (records available through 30 Sep 2010), www.dec.ny.gov/energy/1603.html; [¶]AR: Arkansas Oil and Gas Commission (records available through 30 Sep 2010), www.aogc.state.ar.us/ (data downloaded from: ftp://www.aogc.state.ar.us/).
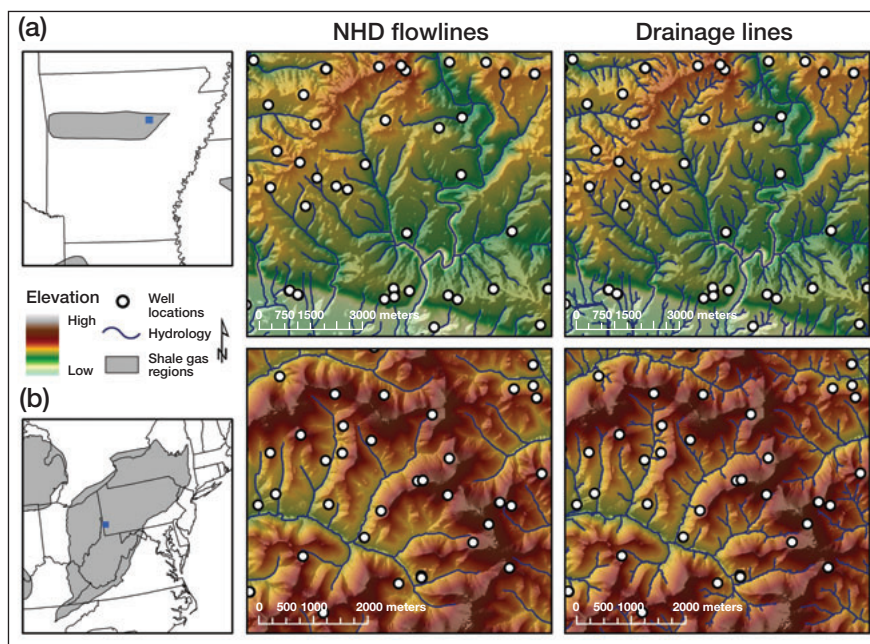
Figure 2. *Proximity of gas wells to stream channels in a subset of the Fayetteville and Marcellus unconventional natural gas reservoirs. Blue squares represent the areas modeled by GIS in the Fayetteville shale ([a] drainage area modeled and represented by the blue square was 5809 km^2) and the Marcellus shale ([b] drainage area modeled and represented by the blue square was 4041 km^2). Topographic maps are example areas that demonstrate differences between the National Hydrography Dataset and modeled drainage area networks.*

active gas wells were located within 300 m of modeled drainage areas (Table 2). Because the modeled drainage areas estimate some intermittent and ephemeral channels, the proximity of wells to stream channels (and the potential for downstream impacts) is greater than that reflected by NHD flowline data. This process may provide a more accurate assessment of potential stream impacts, particularly if shale gas development continues at its current rate. As gas-well densities continue to increase, the proximity of wells to stream channels may also increase, resulting in a greater risk of streamflow reductions from pumping, contamination from leaks and spills from produced waters or

fracking fluids, and sedimentation from infrastructure development (eg pipelines and roads).

■ Environmental regulation

Environmental regulation of oil and gas drilling is complex and varies greatly between states. The Safe Drinking Water Act (SDWA) provides federal laws for protecting surface and groundwaters and human health, but with the exception of diesel-fuel injection, hydraulic fracturing operations are exempt as a result of the 2005 Energy Policy Act. State agencies are therefore primarily responsible for regulation and enforcement of environmental issues associated with natural gas development. The rapid growth and expansion of US gas drilling has made regulation difficult, and violations are common; in Pennsylvania alone, there were more than 1400 drilling violations between January 2008 and October 2010 (PADEP 2010). Of these, nearly half dealt with surface-water contamination and included direct discharge of pollutants, improper erosion control, or failure to properly contain wastes. In contrast, the Arkansas Department of Environmental Quality cited only 15 surface-water violations in the Fayetteville shale in 2010; however, over half of these dealt with permitting and discharge violations associated with natural gas development (ADEQ 2010). The discrepancy in the numbers of violations between states demonstrates the variable degree of regulation at the state level and is probably based on differences in regulations as well as available regulatory resources. The number and proportion of violations associated with natural gas development indicates that sediments

Table 2. Proximity of natural gas wells to stream channels modeled by terrain processing tools in ArcHydro Tools 9 (version 1.3) to generate drainage area lines from a 10-m digital elevation model (http://seamless.usgs.gov/ned13.php) as compared with well proximity to National Hydrography Dataset flowlines

		Subset		Previous distances (in Marcellus, PA only)		Subset			Previous distances (in Marcellus, PA only)		
		range (m)	mean ± SD (m)	range (m)	mean ± SD (m)	within 100 m	within 200 m	within 300 m	within 100 m	within 200 m	within 300 m
Marcellus[*]	Drainage area lines	4–316	153 ± 56	–	–	17%	80%	100%	–	–	–
	NHD flowlines	48–681	252 ± 114	8–1172	319 ± 171	5%	39%	70%	4%	28%	55%
Fayetteville[**]	Drainage area lines	0–420	130 ± 70	–	–	32%	71%	82%	–	–	–
	NHD flowlines	1–933	230 ± 136	7–1642	353 ± 241	12%	43%	61%	10%	32%	51%

Notes: [*]Processed for 615 of 3758 wells (16%), processed 42 of 559 HUC-12 Units containing well point locations (8%). [**]Processed for 2372 of 2834 wells (84%), processed 55 of 84 HUC-12 Units containing well point locations (65%).
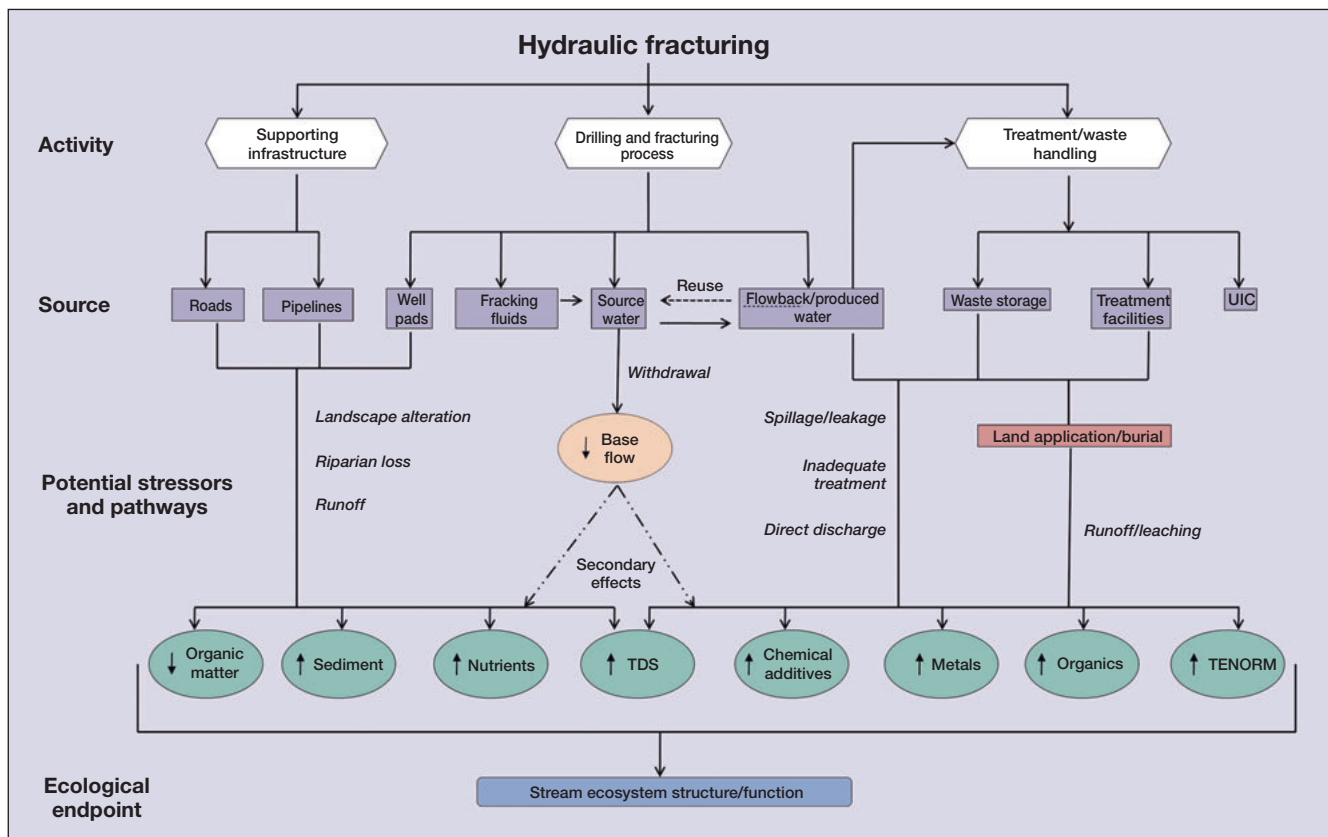
Figure 3. *Simplified diagram of potential threats due to natural gas development through coupled horizontal drilling with hydraulic fluid fracturing in unconventional natural gas reservoirs. Exposure pathways that may result in structural and functional alterations to aquatic ecosystems will vary, depending on geographic location and rigor of best management practices applied. UIC = underground injection control; TDS = total dissolved solids; TENORM = technologically enhanced naturally occurring radioactive materials. Dotted lines indicate secondary effects from gas development. "Flowback" is underlined to indicate that it may be recycled and reused.*

and contaminants associated with drilling are making their way into surface waters, and yet there are few studies examining their ecological effects. Primary threats to surface waters and potential exposure pathways (Figure 3) include sediments, water withdrawal, and release of wastewater.

Sediments

Excessive sediment levels are one of the primary threats to US surface waters (US EPA 2006) and have multiple negative effects in lotic (river, stream, or spring) food webs (Wood and Armitage 1999). Gas-well installation activities can negatively affect lotic ecosystems by increasing sediment inputs from well pads and supporting infrastructure (eg roads, pipelines, stream crossings), as well as loss of riparian area. Typically, at least 1.5–3.0 ha of land must be cleared for each well pad, depending on the number of wells per pad; where these occur in high densities, well pads can cumulatively alter the landscape. Land clearing and stream disturbance during well and infrastructure development can increase sediments in surface-water runoff (Williams *et al.* 2008), resulting in increased suspended and benthic sediments in surface waters. Nutrients, such as phosphorus, bound to these sediments may also have negative impacts on surface waters by contributing to eutrophication.

We identified seven streams in the Fayetteville shale with a variety of different well densities within their drainage areas, to test the prediction that stream turbidity would be positively related to the density of gas wells. The seven stream drainages were delineated through the use of the ArcHydro extension in ArcMap (version 9.3.1 ESRI). Using gas-well location data obtained from the Arkansas Oil and Gas Commission (ftp://www.aogc.state.ar.us/GIS_Files/), we quantified well density within each drainage area as the total number of wells divided by the drainage area. Turbidity was measured with a Hach Lamotte 2020 meter in April 2009, during high spring flow. Pearson product moment correlations identified a positive relationship between stream-water turbidity and well density (Figure 4). Turbidity was not positively correlated to other land-cover variables, but there was a strong negative correlation between turbidity and drainage area and percent pasture cover in the watershed (Table 3). These preliminary data suggest that the cumulative effects from gas well and associated infrastructure development may be detectable at the landscape scale.

Water withdrawal may alter flow regime

Surface waters may serve as sources for necessary drilling and fracking fluids – each well uses between 2–7 million
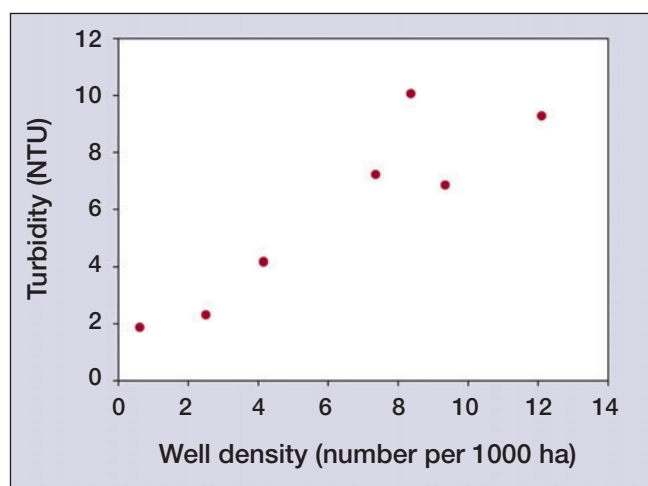
Figure 4. *Well density and stream turbidity measured in April 2009 during high flows in seven stream drainages. NTU = nephelometric turbidity unit.*

gallons (~7.5–26 million liters) of source water. Several wells may be fractured per well pad over the life span of well development, which may last several decades. This concentration of fracturing effort within a small area should compound water use. Many gas wells are installed in regions where water is already being withdrawn for agriculture, and thus may further stress the resource. Streamflow may be negatively affected if streams are dammed to create holding ponds or if water is directly extracted for the fracturing process. The rapid and concentrated extraction of water could create regional shortages during periods of drought, resulting in an altered flow regime and the further degradation of critical habitat for aquatic biota, particularly if low-order streams are primary sources. A reduction in streamflow may also result in secondary effects, such as increased contaminant concentrations and reduced downstream water quality, because less water is available for dilution.

Release of wastewaters

Surface-water contamination from hydrofracking fluids and produced water is most likely to occur during

hydrofracking or treatment and disposal processes, when the potential for accidental spills and leaking is greatest. Contamination from hydrofracking wastes can also occur through inadequate waste treatment practices, improper waste storage, inadequately constructed impoundments or well casings, and improper disposal of solid wastes (eg in poorly lined impoundments that are buried onsite) that may leach into nearby surface waters. Wastewater impoundment ponds can therefore also pose a threat to wildlife and livestock.

Fracturing fluids typically include a combination of additives that serve as friction reducers, cross-linkers, breakers, surfactants, biocides, pH adjusters, scale inhibitors, and gelling agents (NYSDEC 2010). The aim of additives is to achieve an ideal viscosity that encourages fracturing of the shale and improves gas flow, but discourages microbial growth and corrosion that can inhibit recovery efficiency (US DOE 2009). Composition of the fracturing fluids can vary greatly among wells and shale formations. Specific content is often proprietary, although some states require disclosure of constituents and companies may voluntarily register the chemicals they use with regulatory agencies. A recent Congressional investigation revealed that, over a 4-year period, 14 leading gas companies used over 2500 hydrofracking products that contained 750 different chemicals, 29 of which were highly toxic or known carcinogens. Fracturing fluids used over the period totaled 780 million gallons or ~2.9 billion liters (not including dilution water), and included lead, ethylene glycol, diesel, and formaldehyde, as well as benzene, toluene, ethylbenzene, and xylene compounds (US House of Representatives Committee on Energy and Commerce 2011). The volume of fracking fluids recovered is also highly variable, but unrecovered amounts can be substantial. Only 10–30% of fracture fluids are typically recovered from wells in portions of the Marcellus shale (NYSDEC 2010); there is currently no information on the fate and transport of the unrecovered chemicals.

Produced waters pose a threat to surface waters because they typically contain not only fracking additives but also elevated levels of metals, dissolved solids (eg brine), organics, and radionuclides that occur naturally in deep groundwaters. Onsite waste impoundments or evaporation ponds could overflow, spill, or leach into groundwater and contaminate nearby streams. Even after treatment, total dissolved solids (TDS) in produced waters are very high and remaining salts are often disposed of through land application or used as road salts, which are known to enter surface waters and contribute to increased stream salinization (Kaushal *et al.* 2005). Recovered wastewaters are most often transported offsite for deep-well injection or to a domestic wastewater treatment plant (WWTP) and/or conventional waste treatment facility. After fracturing, initially recovered flowback water is sometimes reused as fracking fluid for other wells. Reuse of recovered fluids is becoming more common, but

Table 3. Pearson product moment correlations[*] and associated *P* values between turbidity (NTU) and other landscape-level variables, including land cover (Gorham and Tullis 2007) and drainage area

Correlates	r	P value
Well density	0.91	0.003
Drainage area	−0.86	0.01
Low-impact urban	0.35	0.44
Wood/herbaceous	−0.63	0.12
Forest	−0.36	0.42
Pasture	−0.88	0.008

[*]Quantifies the strength of the directional relationship. Analyses were run in SigmaPlot 11.

still requires a substantial amount of fresh water because of low recovery volumes and the need to dilute flowback water containing high concentrations of chlorides, sulfates, barium, and other potentially harmful substances. Domestic WWTPs are not capable of treating the high TDS (5000 to >100 000 mg L^{-1}) typical of recovered wastewater. Many WWTPs have therefore been forced to limit their intake of recovered hydrofracking waste to remain in compliance with effluent limitations (Veil 2010). Industrial WWTPs are better equipped to treat recovered wastes using reverse osmosis, filtration, or chemical precipitation, but such facilities are costly and not widely available. Therefore, although billions of liters of produced water are being generated annually on a national scale by hydrofracking (Clark and Veil 2009), water treatment options are limited, and the potential ecological impacts of wastes on terrestrial and aquatic ecosystems are not well studied.

■ Challenges and potential for new research

Quantifying the effects of natural gas development on surface waters in shale basins is difficult because multiple companies often work in the same geographical area and use different fracturing techniques (eg varied and often proprietary composition of fracturing fluids), resulting in uncoordinated timing of infrastructure development and well fracturing. In addition, the degree to which these companies adhere to best management practices, such as buffer strips and erosion control devices, varies among companies as a result of the differing regulations among states and agencies. Furthermore, wells occur across human-impacted watersheds with characteristics that may confound our ability to attribute effects from gas-well development.

Most studies that examine the effects of sediments on biological communities focus on shifts in abundance, biomass, diversity, or community composition (Wood and Armitage 1999); few studies have analyzed how sediments alter species' roles and their interactions (but see Hazelton and Grossman 2009). In addition, contaminant effects are often assessed through single-species laboratory acute and chronic toxicity tests with standardized test organisms (eg *Daphnia*, fathead minnows [*Pimephales promelas*]; Cairns 1983) and with single contaminants. Studies are therefore needed to assess the toxicity of contaminant mixtures (eg produced water and fracking fluids) and their effects on more complex communities and ecosystems, to predict effects in the real world (Clements and Newman 2002). Sediment and contaminants associated with recovered wastewater will likely affect organism behavior and alter ecological interactions at sublethal levels (Evans-White and Lamberti 2009). Reductions in feeding efficiencies (Sandheinrich and Atchison 1989) can lead to negative effects on reproduction (Burkhead and Jelks 2001) and growth (Peckarsky 1984), and may alter the magnitude or sign (+ or –) of species' effects, causing changes in community structure. Ecologists studying the environmental effects of natural gas extraction can therefore contribute to scientific understanding by examining the effects of sediment and contaminants from natural gas development on species and community interactions.

In addition to the need for traditional bioassessments, the inevitable alteration in land use that will occur as a result of rapid and expanded drilling offers a template for conducting novel experiments in an ecosystem context. Ecosystem functions, such as decomposition rates, are affected by multiple abiotic and biotic factors, making them well-suited for detecting large-scale alterations (Bunn *et al.* 1999). For example, reduced streamflows, contaminants from produced wastewater and fracking fluids, and elevated sediment inputs would alter ecosystem functions, such as whole-stream metabolism, decomposition of organic matter, and accrual of macroinvertebrate biomass over time. However, it is not known how natural gas development could influence biological processing rates. The potential effects may stimulate or inhibit specific ecosystem functions. For example, excessive sedimentation or chemical contamination associated with natural-gas-well development could stimulate macroinvertebrate production by expanding habitat for tolerant, multivoltine (species that produce several broods per season) taxa (Stone and Wallace 1998) or lead to a decline in production by eliminating sensitive taxa representing a majority of community growth and/or biomass (Woodcock and Huryn 2007). A move to incorporate ecosystem functions into mainstream biological assessment and restoration protocols is currently underway (Fritz *et al.* 2010), yet few studies have been conducted to inform their implementation and interpretation in the context of concurrent structural changes (Young and Collier 2009). The rapid expansion of gas development across the US could provide a framework for the implementation of concurrent structural and ecosystem experiments to inform process-based ecological assessment. Furthermore, ecological studies relating to natural gas extraction could be combined with similar studies for surface mining (Fritz *et al.* 2010; Bernhardt and Palmer 2011), to gain a more holistic view of the environmental costs associated with fossil-fuel extraction.

The distinct elemental composition and isotopic signatures of produced water provide unique opportunities for tracer studies that could indicate aquatic system exposure. Stable isotopes of strontium and carbon have been used to trace water from coalbed natural gas production wells to surface waters and hyporheic zones (Brinck and Frost 2007). Osborn *et al.* (2011) used isotopes of water, carbon, boron, and radium to test for hydraulic fracturing contamination of shallow aquifers overlying the Marcellus and Utica shale formations in Pennsylvania and New York, respectively, and found significant changes in CH$_4$ concentrations in drinking-water wells near locations where gas wells have been drilled. Limited

research has also suggested that CH_4-derived carbon is assimilated into stream food webs (Kohzu *et al.* 2004; Trimmer *et al.* 2010). Many gas-bearing geological formations also contain elevated levels of naturally occurring radioactive materials, such as radon (^{222}Rn) and radium (^{226}Ra, ^{228}Ra), that can be used as hydrological tracers (Genereux and Hemond 1990). The extent to which metals, organics, or other contaminants from the drilling and hydrofracking process may ultimately enter aquatic and terrestrial food webs remains unknown.

■ Conclusions

Natural gas exploration will continue to expand globally. In addition to the potential threats to groundwater and drinking-water sources, increasing environmental stress to surface-water ecosystems is of serious concern. Scientific data are needed that will inform ecologically sound development and decision making and ensure protection of water resources. Elevated sediment runoff into streams, reductions in streamflow, contamination of streams from accidental spills, and inadequate treatment practices for recovered wastewaters are realistic threats. Gas wells are often sited close to streams, increasing the probability of harm to surface waters, and preliminary data suggest the potential for detectable effects from sedimentation. Regulations that consider proximity of natural gas development to surface waters may therefore be needed. Further ecological research on impacts from developing natural-gas-well infrastructure are sorely needed, and will inform future regulatory strategies and improve our understanding of the factors affecting community structure and ecosystem function.

■ Acknowledgements

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