Biotic impacts of energy development from shale: research priorities and knowledge gaps

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Although shale drilling operations for oil and natural gas have increased greatly in the past decade, few studies directly quantify the impacts of shale development on plants and wildlife. We evaluate knowledge gaps related to shale development and prioritize research needs using a quantitative framework that includes spatial and temporal extent, mitigation difficulty, and current level of understanding. Identified threats to biota from shale development include: surface and groundwater contamination; diminished stream flow; stream siltation; habitat loss and fragmentation; localized air, noise, and light pollution; climate change; and cumulative impacts. We find the highest research priorities to be probabilistic threats (underground chemical migration; contaminant release during storage, during disposal, or from accidents; and cumulative impacts), the study of which will require major scientific coordination among researchers, industry, and government decision makers. Taken together, our research prioritization outlines a way forward to better understand how energy development affects the natural world.

Rapid development of fossil-fuel resources has the potential to transform landscapes and biological communities before the resulting impacts are fully understood. In the US, the extraction of gas and oil reserves trapped in shale rock (known as "shale-gas" and "tight oil", respectively) through hydraulic fracturing (also called "fracking" or "hydrofracking") has grown exponentially since 2007 (Figure 1; EIA 2011). Such technology exploits previously inaccessible natural gas reserves through the deep injection of high-pressure aqueous chemicals into shale rock to create fractures, releasing trapped gas (Figure 2; see "Additional references" section in the web-only materials [WOM]). Although this tech-

nology is well studied (with >1000 peer-reviewed publications), surprisingly little research has focused on the biotic impacts of shale development. While the biological effects of other methods for extracting fossil fuels are better understood, these studies generally lack clear mechanistic links to fuel extraction and are limited to a small number of species, countries, and ecoregions (Northrup and Wittemyer 2012). Moreover, shale development differs from other forms of fossil-fuel extraction in multiple ways, including a broad and diffuse geographic footprint and an extremely high water demand. Therefore, many of the biotic impacts of shale development are unique and cannot be inferred from knowledge of other forms of oil and natural gas extraction.

Understanding the impacts of shale development is essential because many shale basins, particularly those in the eastern US, occur in regions of exceptional biological diversity (Figure 3); for instance, the most rapidly growing source of natural gas in the US (ie the Marcellus Shale in the Appalachian Basin) underlies one of the country's highest diversity areas for amphibians and freshwater fish (Collen *et al.* 2013). In the US and Europe (Figure 4), shale basins often overlap with areas already experiencing severe threats to freshwater resources. In conjunction with other anthropogenic activities, environmental change associated with shale operations may cumulatively affect living organisms in unknown, potentially calamitous, ways.

Here, we identify and prioritize research needs related to shale development using a quantitative framework. We consider the entire process of shale development, examining the threats to animals and plants from site development and maintenance, water sourcing, well operation and fracturing, and storage and disposal of injection fluids (Figure 2). We classify impacts as probabilistic (ie

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In a nutshell:

- Exploitation of oil and gas reserves trapped in shale rock, including the extraction process known as "fracking", poses substantial and unexplored risks to living creatures
- Understanding the biotic impacts of operations that fracture shale to access reserves is hindered by the unavailability of high-quality data about fracturing fluids, wastewater, and spills or violations
- The risks of chemical contamination from spills, deep well failures, storage leaks, and underground fluid migration are top research priorities
- Cumulative effects of shale development may represent the most severe threats to plants and animals, but are particularly challenging to study

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unplanned or accidental) or deterministic (ie planned or unavoidable) following the structure developed by Rahm and Riha (2012). Our focus is on biota because plants, animals, and other living organisms have largely been omitted from other reviews, which tend to emphasize abiotic effects (eg Entrekin *et al.* 2011; Howarth *et al.* 2011a), and because shale formations often lie beneath global hotspots of species diversity. Our goal is to improve research of the biotic impacts associated with shale development by prioritizing research needs and highlighting associated challenges.

■ Prioritization scheme

We assessed potential effects of shale development on living organisms based on four criteria: current understanding, spatial extent, temporal extent, and mitigation difficulty (Table 1). For each impact, we ranked current understanding as low, medium, or high and assigned a corresponding value of 3, 2, or 1 (where 3 is low understanding, suggesting high research needs) based on the number of relevant studies (additional methods provided in WebPanel 1). The three remaining risk-based criteria were assigned values of 1, 2, or 3, corresponding to low, medium, or high ratings (where 3 represents high risk to biota for a criterion). For each impact, the research priority was calculated by averaging criteria values, where current understanding was weighted by a factor of 3 to reflect the importance of existing scientific information in determining research needs. Average values corresponded to final rankings as follows: low (1.0–1.5), medium-low (1.6–1.9), medium (2), medium-high (2.1–2.5), and high (>2.5).

■ Probabilistic impacts

Probabilistic impacts to biota from shale development do not occur as an unavoidable outcome of development but do occur with a certain frequency. Although some of these impacts may be rare occurrences (ie the result of "unexpected" events), because most relate to the release of potentially toxic chemicals into the environment, the possibility of biotic harm can be great.

Underground migration of contaminants

During well fracturing, chemicals suspended in an aqueous medium are injected under high pressure into shale to release natural gas. Fracturing fluid generally includes a mix of acids, biocides, friction-reducing agents, and other chemicals to facilitate gas retrieval (Vidic *et al.* 2013). Many of the chemicals (eg methanol, xylene, naphthalene, hydrochloric acid, toluene, benzene, and formaldehyde) are regulated in the US by the Safe Drinking Water Act, the Clean Water Act (40 CFR Section 401.15), or the Clean Air Act (US EPA 2012) and have been linked to negative health effects in humans (Colborn *et al.* 2011). Releases of fracking fluid into streams have
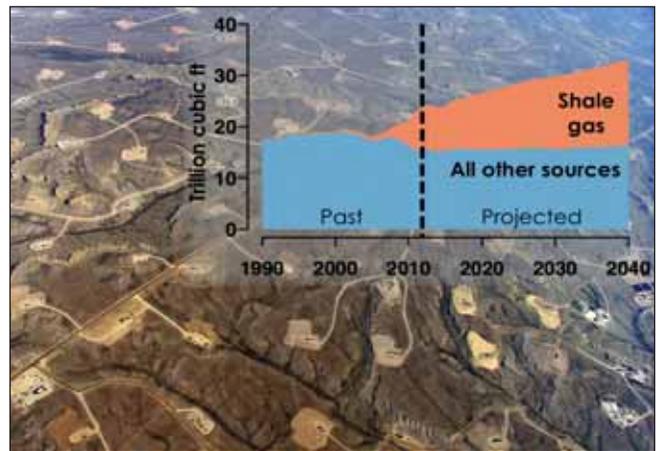

Figure 1. *Proliferation of natural gas wells in the Jonah Field, Wyoming, US. Inset: historical and predicted natural gas production in the US. Data from EIA (2011).*

resulted in direct mortality and stress of fish and aquatic invertebrates (Papoulias and Velasco 2013). A proportion of this fluid – the amount varies substantially among geologic formations, but can be as high as 90% – remains underground after its application (Entrekin *et al.* 2011; Vidic *et al.* 2013). The fate and potential biotic impacts of unrecovered fracturing fluids are highly uncertain.

Due to the depth of most hydraulically fractured shale-gas formations (900–2800 m; Vidic *et al.* 2013), the contamination of groundwater by subsurface migration of fracturing fluid is considered unlikely (Engelder 2011; Vidic *et al.* 2013). Nevertheless, geologic pathways for chemical migration have been identified (Warner *et al.* 2012). Moreover, drinking water contamination with fracturing chemicals and/or methane (CH_4) has been reported (DiGiulio *et al.* 2011; Osborn *et al.* 2011; Jackson *et al.* 2013), although some of these studies have been criticized as providing insufficient evidence to attribute water contamination to shale development (eg Davies 2011). Future research must determine whether hydraulic fracturing causes CH_4 contamination and whether, in the absence of equipment failure and accidents, chemicals do migrate from fractured shale beds. Given the limited understanding (WebTable 1) of the likelihood, frequency, and spatiotemporal extent of such contamination events, and the few options for mitigation, this is a high research priority (Table 1).

Contamination from equipment failure, illegal activities, and accidents

In addition to chemical migration from fractured shale, freshwater contamination may result from well blowouts, casing failures, illegal discharge, and spills during fluid transport and storage (Figure 2). Many such contamination events involve the release of recovered fluid (called "produced water"), which consists of fracturing fluid and salts, heavy metals, hydrocarbons, and radioactive material accumulated from natural underground sources (Howarth *et al.* 2011a). The high saline content of recovered fluid
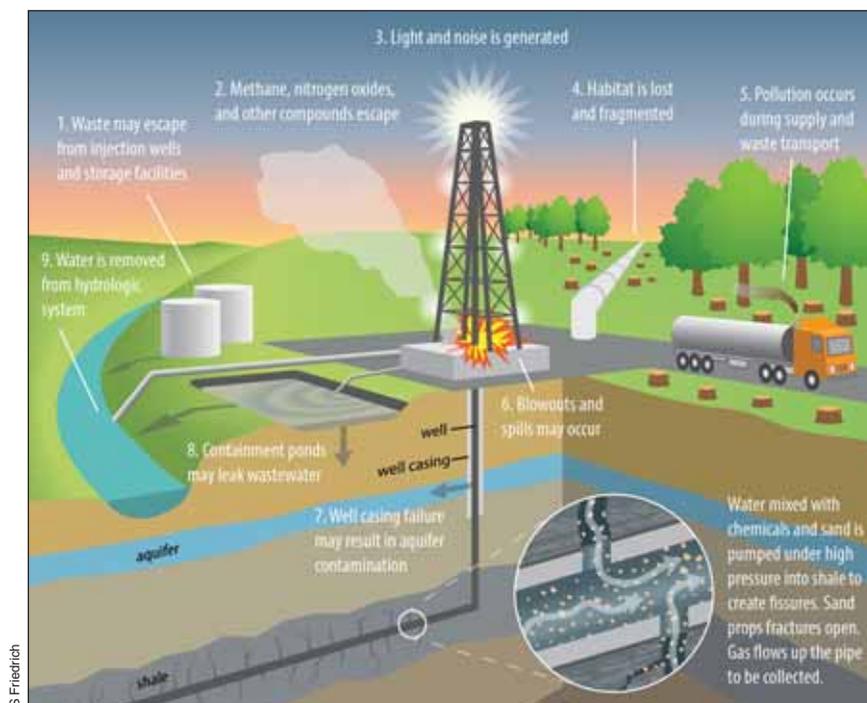
Figure 2. *Shale development includes multiple processes focused around natural gas extraction via hydraulic fracturing. Impacts of shale development on biota can include probabilistic (1, 6, 7, 8) and deterministic (2, 3, 4, 5, 9) effects of these various processes. Contamination of aquatic and terrestrial systems may occur due to spills, leaks, or accidents during hydraulic fracturing (6), waste storage (1, 8), and transport (5). Permanent removal of water from the hydrologic cycle and subsequent effects on water quality (9), habitat loss and fragmentation (4), and air (2) and noise and light (3) pollution are unavoidable consequences of shale development, although technological advances and appropriate planning can minimize biotic effects. Shale development contributes to climate change in various ways, including CH_4 release during well venting (2) as well as fossil-fuel use during site development, well fracturing, and waste disposal (eg 5).*

alone poses risks to biota, given that increases in salinity of as little as 1 g L^{-1} can harm or kill aquatic plants and invertebrates (Hart *et al.* 1991).

Currently, the frequency and extent of freshwater contamination due to spills, accidents, and violations is poorly quantified. Of the 24 US states with active shale gas reservoirs, only Pennsylvania, Colorado, New Mexico, Wyoming, and Texas maintain public records of spills or violations for oil and gas drilling operations. We examined the frequency and nature of violations in the Pennsylvania Department of Environmental Protection's (PADEP's) oil and gas management compliance-reporting database (data analyzed in WebTable 2). A total of 523 violations at 279 permitted wells were detected in 2013, representing ~2.5% of inspections (12 452 total) and 5% of wells (5580 total). The three most common violations included: failure to properly store, transport, process, or dispose of residual waste ($n = 85$); failure to adopt required or prescribed pollution prevention measures ($n = 48$); and failure to plug a well upon abandonment ($n = 43$). Spills were detected at 37% of wells found in violation and were generally small (median = 265 L; range = 4–43 000 L), although there were nine spills of over 3500 L. Spills typ-

ically occurred on the well pad, with nearly 20% of reports documenting contamination of land or surface water. Location (on-pad versus off-pad) was specified in fewer than half of the reports (42%), and spatial extent of contamination was rarely (5%) described. The time between the spill and reporting was noted in <10% of cases (median = 5.75 hours; range = 1 hour to 6 weeks). In addition to the lack of data describing the nature and extent of spills, spill frequency was probably underestimated. Many reports were ambiguous, and companies routinely violated Pennsylvania's reporting requirement (only 59% of documented spills were reported by the drilling company). Collectively, poor data quality and lack of consistent reporting represent a major obstacle to understanding the impacts of chemical contamination from shale development. Ecological impacts of spills and accidents are also a high research priority, given the limited knowledge, the potential for lasting and widespread adverse environmental consequences, and the difficulty in mitigating such contamination events.

Release of contaminants during waste storage and disposal

As in the case of contamination from spills and accidents, lack of data on wastewater disposal impedes environmental assessment. Waste volume, composition, and fate vary among drilling companies, states, and geologic formations (Entrekin *et al.* 2011; Rozell and Reaven 2011; Rahm and Riha 2012; Rahm *et al.* 2013). Industry-reported data from PADEP revealed a 570% increase in wastewater production since 2004 from development of the Marcellus Shale (Maloney and Yoxtheimer 2012; Lutz *et al.* 2013). Drill cuttings were principally disposed of in landfills, and wastewater (ie recycled fluid) was most frequently treated at industrial facilities or injected into deep wells (a large proportion of wastewater was re-used prior to disposal; Maloney and Yoxtheimer 2012). Risk of waste migration from deep injection wells to freshwater aquifers is poorly understood and, notably, deep well injection has been linked to increased seismic activity (Frohlich *et al.* 2011). Containment ponds frequently serve as temporary wastewater storage at drilling sites, and these vary substantially in structural integrity. Inadequately designed ponds can overflow during heavy rain, may leak as liners degrade, are accessible to wildlife, and are potential sources of air pollution as chemicals volatilize (Entrekin *et al.* 2011). While the frequency of containment pond failure has not been quantified, our in-

vestigation of Pennsylvania's 2013 well inspection data (described above) detected numerous violations (eg 27 violations citing "Pit and tanks not constructed with sufficient capacity to contain pollutional substances"), indicating that some containment facilities fail to prevent escape of contaminants. Inappropriate management of waste products, including the direct discharge of industrial waste into streams, comprised 34% of the total violations issued by PADEP (WebTable 2).

There is virtually no empirical information about the biotic risks associated with disposal of produced water and drill cuttings (WebTable 1). Given this paucity of data, the unquantified spatial and temporal extent of contamination, and few mitigation options, the pathways and consequences of environmental contamination from waste storage and disposal represent high research priorities (Table 1). A critical first step in this research is improving basic reporting to generate accurate data describing waste composition and fate. For each method of wastewater disposal, future research should determine the concentration of toxins released into the environment, exposure duration and potential pathways (eg ingestion, inhalation, or contact), and the effects on aquatic and terrestrial biota. A general evaluation of current above- and belowground remediation strategies is needed to address whether current technologies are capable of removing contaminants and what site characteristics enhance or preclude effective remediation.

Disclosure of fracturing chemicals

Although not a biotic impact on its own, the lack of disclosure regarding many fracturing chemicals can hamper the ability of researchers to understand, predict, and mitigate adverse environmental effects. Certain chemicals in fracturing fluids are classified as confidential business information under Section 14(c) of the US Toxic Substances Control Act (US EPA 2012). Many companies have vol-

untarily disclosed non-proprietary fluid components, and ten states currently participate in the FracFocus (www.fracfocus.org) national registry as a means of chemical disclosure. We investigated the proportion of proprietary components for 150 randomly selected wells representing three of the top producing states (ie Texas, Pennsylvania, and North Dakota) in the registry (data presented in WebTable 3). Overall, 67% of wells in our sample were fractured with fluid containing at least one undisclosed chemical, and 37% were fractured with five or more undisclosed chemicals. Some wells (18%) were fractured with a complex fluid containing 10 or more undisclosed components. Importantly, many disclosed chemicals lacked Chemical Abstracts Service (CAS) numbers or concentration values. Most wells (82%) were fractured with fluid containing either undisclosed components or disclosed chemicals lacking this information. Chemical

Table 1. Research priorities based on the relative extent, difficulty mitigating, and current understanding of potential impacts

Source of ecological impact	Type of occurrence*	Spatial extent**	Temporal extent	Mitigation difficulty	Current understanding‡	Research priority‡
Underground migration of contaminants	Probabilistic	Unknown (3)	Unknown (3)	High (3)	Low (3)	High (3.0)
Contamination of surface water from equipment failure, illegal activities, and accidents	Probabilistic	Unknown (3)	Unknown (3)	High (3)	Low (3)	High (3.0)
Release of contaminants during waste storage or disposal	Probabilistic	Unknown (3)	Unknown (3)	High (3)	Low (3)	High (3.0)
Cumulative impacts	Probabilistic	Unknown (3)	Unknown (3)	Unknown (3)	Low (3)	High (3.0)
Land application of wastewater	Deterministic	Low (1)	Medium (2)	Medium (2)	Low (3)	Medium-High (2.3)
Climate-change contribution	Deterministic	High (3)	High (3)	High (3)	High (1)	Medium (2)
Habitat loss/fragmentation	Deterministic	High (3)	High (3)	Medium (2)	High (1)	Medium-Low (1.8)
Diminished stream flow	Deterministic	Medium (2)	Medium (2)	Low (1)	Medium (2)	Medium-Low (1.8)
Air pollution	Deterministic	Low (1)	Low (1)	Medium (2)	Medium (2)	Medium-Low (1.7)
Siltation	Deterministic	Medium (2)	Medium (2)	Medium (2)	High (1)	Low (1.5)
Noise pollution	Deterministic	Low (1)	Low (1)	Low (1)	High (1)	Low (1.0)
Light pollution	Deterministic	Low (1)	Low (1)	Low (1)	High (1)	Low (1.0)

Notes: *Following Rahm and Riha (2012). **Values in parentheses correspond to numerical rankings, as explained in text. Box color reflects the severity of each criterion, from minor (blue) to severe (orange). †Weighted by a factor of 3 to reflect importance of current knowledge in determining research priorities. ‡Final rankings in parentheses correspond to weighted average of individual rankings.

information was sometimes omitted for "non-hazardous" components, but chemicals that are innocuous to humans (eg some salts) can be lethal to freshwater organisms. No chemical information was provided for produced water, making it impossible to formulate these reclaimed fluids for experimental research. A centralized source of chemical information would greatly facilitate research. The current FracFocus registry has major limitations, including: incomplete state participation; failure to consistently provide concentrations and CAS numbers for disclosed chemicals; and non-disclosure of a substantial proportion of chemicals. Because compounds in mixtures can have synergistic or antagonistic effects (Altenburger *et al.* 2003), full chemical disclosure of fracturing fluid and wastewater is essential for understanding the associated risks to biota, including the effects of leaks, spills, and direct terrestrial or aquatic application.

Cumulative impacts

The biological impacts of shale energy development are numerous, and include water scarcity, habitat loss, and various forms of pollution (see "Deterministic impacts" section below). Many of these threats (Figure 2) cross terrestrial and aquatic boundaries, extend beyond the immediate footprint of the operation, and may interact to affect ecosystems in unexpected ways. Given that the overall impact of shale development will likely outweigh that of any individual stage of the process, risk assessments should incorporate cumulative impacts on biota. Importantly, this assessment framework should be extended to consider the contributions of unrelated but co-occurring stressors (eg resource extraction or residential development).

The few studies that consider cumulative impacts suggest that shale-gas development will affect ecosystems on a broad scale (Kiesecker *et al.* 2009; Jones and Pejchar 2013; Evans and Kiesecker 2014). For example, Evans and Kiesecker (2014) found that energy development – primarily from shale – in a large portion of the Marcellus Shale could result in the construction of >500 000 ha of impervious surface, leaving >400 000 ha of affected forest. Given the overall absence of knowledge regarding cumulative impacts, and the potential for synergistic, negative interactions of shale-gas development impacts on ecosystems, this area represents another high research priority (Table 1). Using a cumulative-impacts framework, researchers should specifically address how the density and spatial configuration of shale wells interact with the timing and frequency of drilling operations (eg water withdrawals or site clearing) to develop strategies for minimizing negative biological impacts. As cumulative impacts' methodology and knowledge improve, research should move toward detecting synergies between shale development and other likely drivers of extinction, such as climate change, as site-specific or single variable risk assessments likely underestimate threats to ecological health.

◼ Deterministic impacts

Most of the foreseeable ecological impacts of shale development (eg pollution, habitat loss, siltation) are also associated with other forms of anthropogenic disturbance. While much knowledge can (and should) be drawn from other disciplines, certain aspects of shale development have unique temporal, geographic, spatial, and/or mechanistic attributes. The challenge for the scientific community is to determine what new information is needed to understand and mitigate these impacts in the specific context of shale development.

Siltation and diminished stream flow

Only 21% of river and stream length in the US is in "good biological condition", and major threats to freshwater biota include siltation and water extraction (US EPA 2013b). Quantifying the effect of shale development on siltation is difficult, but the factors that determine siltation (eg well density and proximity to surface waters) are relatively well studied. In the US, more than 6000 rivers are impaired as a result of sediment pollution (US EPA 2014), and the causes, consequences, and mitigation of siltation have been studied for decades (Berkman and Rabeni 1987; Donohue and Garcia Molinos 2009; Gellis and Mukundan 2013). The contribution of shale development to sediment load will vary geographically, depending on local hydrology, geology, and existing forms of land disturbance. In the Marcellus region, habitats affected by shale development are likely to include lower-order (eg headwater) streams with relatively little sediment input from other sources (Olmstead *et al.* 2013). Given the extensive amount of relevant scientific literature about stream siltation (WebTable 1), the moderate spatial and temporal extent of this problem, and the existence of well-developed mitigation strategies as compared with other impacts, this threat is a low research priority (Table 1).

While many forms of land use contribute to siltation, shale development consumes an exceptionally large quantity of fresh water. An average of nearly 20 million L of water is required to fracture a shale well over its lifetime (Entrekin *et al.* 2011; Howarth *et al.* 2011a). Given this massive water demand, well pads are typically constructed near freshwater sources. As of September 2010, more than 750 shale wells had been drilled within 100 m of rivers and streams in five eastern US states (Entrekin *et al.* 2011), and nearly 4000 wells drilled within 300 m of these freshwater habitats (Entrekin *et al.* 2011). The close proximity of well sites to freshwater sources exacerbates the risk of chemical contamination and sedimentation of aquatic ecosystems (Gregory *et al.* 2011). Water extraction can substantially alter local hydrology by reducing stream water levels and flow rates, which can result in warmer water temperatures, increased concentrations of pollutants, and less dissolved oxygen for aquatic life.

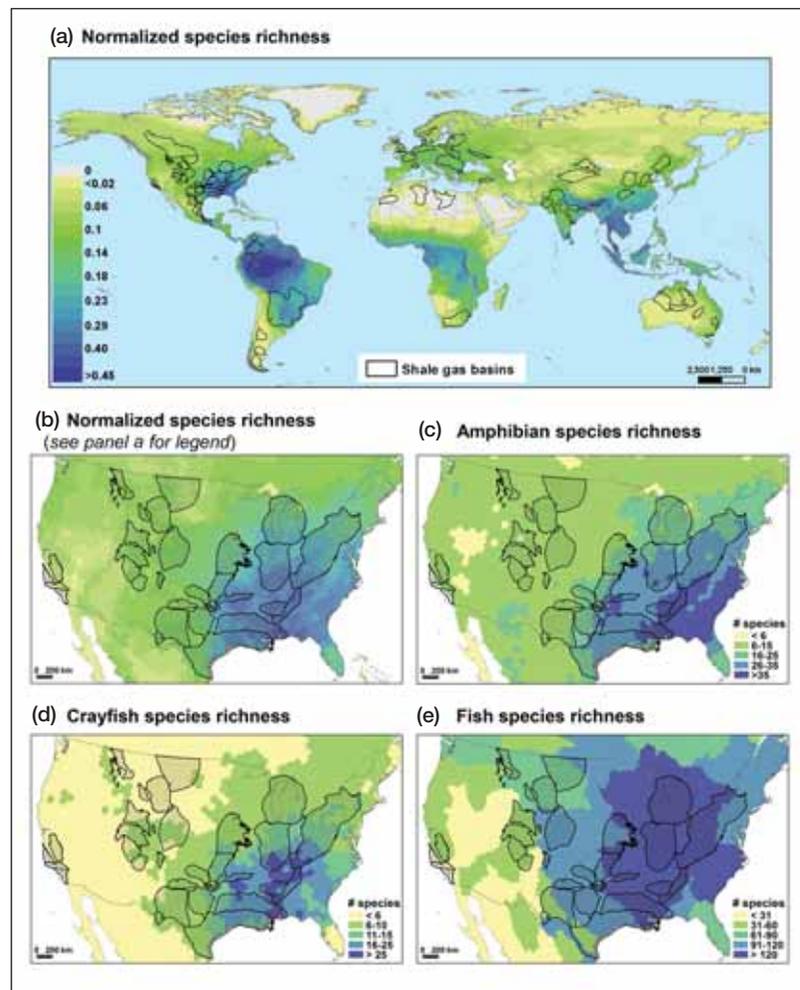Certain aspects of freshwater removal for hydraulic frac-

turing are unique (ie volume and geographic pattern of water withdrawals). Although in-stream flow is well studied in other contexts, there is virtually no relevant empirical data for shale development (WebTable 1). Given the modest level of scientific understanding, potential ease of mitigation (eg by restricting water withdrawals), and relatively moderate spatial and temporal extent, this threat repre-sents a medium to low priority for research (Table 1). The minimum stream flow rates and water volumes necessary to sustain bio-logical function will vary among habitats and life stages, and should be studied at fine spa-tial scales.
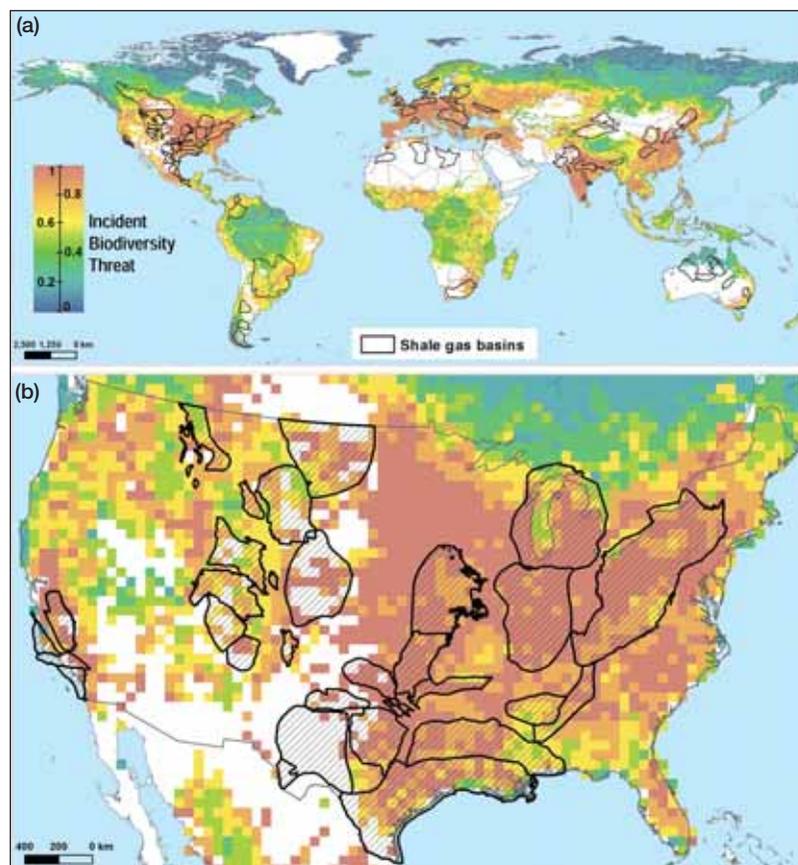
Habitat loss and fragmentation

Construction of wells and associated infra-structure (eg access roads, pipelines) disrupts habitat. On average, 1.5–3.1 ha of vegetation are cleared during the development of a sin-gle well pad (Entrekin *et al.* 2011). Although this footprint is relatively small, the vast number of shale wells equates to considerable habitat loss. Furthermore, the amount of land cleared for pipelines and other infrastructure can far exceed that of the well pad (Slonecker *et al.* 2012). In Pennsylvania's Bradford and Washington counties (together representing ~280 000 ha of forest), shale-drilling operations disturbed nearly 2500 ha of land between 2004 and 2010, and dispro-portionally affected the interior forests that provide important habitat for rare species (Slonecker *et al.* 2012); in the Susquehanna River basin, more than one-quarter of shale well pads were constructed in previously intact forest habitat (Drohan *et al.* 2012). In the western US, natural gas development has decreased secure habitat for pronghorn (*Antilocapra americana*; Bechmann *et al.* 2012) and mule deer (*Odocoileus hemionus*; Sawyer *et al.* 2009), and disrupted breeding sagebrush bird communities (Gilbert and Chalfoun 2011) including greater sage-grouse (*Centrocercus urophasianus*; Webb *et al.* 2012).

Well pads and infrastructure result in major habitat frag-mentation. Shale development in known basins (Figures 3 and 4) threatens to disrupt ~500 natural corridors in west-ern North America (Theobald *et al.* 2012). Such corridors are crucial to maintaining healthy wildlife populations in a changing climate (Lawler *et al.* 2013). While fragmentation effects of shale development have been poorly studied (Northrup and Wittemyer 2012), fragmentation from any source can reduce dispersal, foraging, and mating success, thereby increasing species' risk of local extinction (Aguilar

Figure 3. Freshwater biodiversity in relation to the extent of shale gas basins: normalized species richness (a) globally and (b) within the US; US-only (c) amphibian species richness, (d) crayfish species richness, and (e) fish species richness. Biodiversity data (a–d) were derived from Collen et al. (2013); data in (e) were derived from Hoekstra et al. (2010; downloaded from www.databasin.org and used under a Creative Commons Attribution 3.0 License, http://creativecommons. org/licenses/by/3.0). All freshwater biodiversity data are shown in relation to the extent of shale gas basins assessed by the US Energy Information Administration (www.eia.gov) and represent known extents as of May 2011; countries/regions included in the global shale gas assessment are: Mexico, Canada, Colombia, Venezuela, Argentina, Chile, Uruguay, Paraguay, Bolivia, Brazil, Algeria, Tunisia, Libya, South Africa, France, Germany, Netherlands, Norway, Denmark, Sweden, the UK, Poland, Ukraine, Lithuania, Romania, Bulgaria, Hungary, China, India, Pakistan, Turkey, and Australia.

et al. 2006; Fischer and Lindenmayer 2007). The resulting edge habitat generally benefits common and generalist species at the expense of rare and more vulnerable species (Ries *et al.* 2004). Opening of formerly remote areas can facilitate poaching of imperiled and sensitive species, serve as a conduit for invasive and non-native species (including pathogens), and provide a gateway to further and more per-manent development (Fahrig 2003). Although habitat loss and fragmentation occur on broad scales and are moder-ately difficult to mitigate, these processes are relatively well studied (WebTable 1) and represent a medium-low research

Figure 4. (a) Global and (b) US distribution of pre-existing threats to freshwater biodiversity in relation to the extent of shale gas basins. The Incident Biodiversity Threat index for freshwater biodiversity was derived by Vörösmarty et al. (2010; downloaded from www.databasin.org and used under a Creative Commons Attribution 3.0 License, http://creativecommons.org/licenses/by/3.0), and ranges from 0 (lowest threat) to 1 (highest threat). Areas in white denote regions with an average annual runoff <10 mm (see supplementary materials from Vörösmarty et al. [2010] for full description).

references" in the WOM). In addition to their direct toxicity, NO_x and VOCs contribute to ozone (O_3) formation. Natural gas operations emit nearly 30 times the VOCs as compared with coal operations, primarily during extraction and transport (US EPA 2013a). Ground-level O_3 is a strong pulmonary and respiratory irritant in mammals (Watkinson *et al.* 2001) and negatively affects growth, reproduction, and survival of plants (Karnofsky *et al.* [2005] and references within). Dangerous concentrations of surface O_3 have been detected near large oil and gas operations (Martin *et al.* 2011), including in winter (Carter and Seinfeld 2012). As O_3 pollution is normally a warm-weather problem, its potential impacts on animals and plants as a year-round phenomenon are entirely unknown.

Given the limited scale of noise and light pollution, along with the ease of mitigation and relatively well-developed state of knowledge, these threats are low research priorities (Table 1). Air pollution is a slightly higher (medium to low) research priority because it is more challenging to mitigate; thus, aspects unique to shale development warrant further study (eg wintertime O_3).

Climate-change contribution

Shale development will affect biota indirectly, but substantially, through climate change. These impacts occur primarily through the routine venting of CH_4 during well fracturing, but also from the release of carbon dioxide (CO_2) and other greenhouse gases during site development, fracturing, and waste disposal (Howarth *et al.* 2011b, 2012; Petron *et al.* 2012). Climate change poses one of the greatest global threats to biota (Thomas *et al.* 2004), has spatially and temporally expansive impacts, and is extremely challenging to mitigate. However, because greenhouse gases and the chemical basis for climate change are well understood (WebTable 1), we rank this threat as a medium research priority in the context of shale development (Table 1).

Land application of wastewater

As of 2011, certain states – including West Virginia, Arkansas, and Colorado – permitted wastewater disposal via direct application to land or roadways, often as a de-icing agent (Adams 2011). Direct land application guarantees immediate and widespread contamination of ecosystems. Land application of wastewater has caused rapid, complete mortality of vegetation and 56% mortality of trees within 2 years (Adams 2011). Other research supports these findings and indicates that even low concentration of wastewater

priority (Table 1). Notably, however, new extraction techniques have made it economical to develop historically unprofitable gas reserves, threatening terrestrial biota in formerly intact areas (Northrup and Wittemyer 2012). Moreover, the diffuse, branching pattern of habitat loss associated with hydraulic fracturing distinguishes it from other forms of land-use change (Northrup and Wittemyer 2012).

Light, noise, and air pollution

Shale operations create light, noise, and air pollution. Anthropogenic light and noise can negatively affect fitness across a broad group of species, including mammals, amphibians, birds, insects, and aquatic invertebrates (see "Additional references" in the WOM). Noise pollution generated by natural gas extraction causes some avian species to avoid breeding sites (Blickley *et al.* 2012), resulting in reduced bird abundance (Bayne *et al.* 2008). Shale operations emit nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter, each of which is harmful to biota (see "Additional

can alter species composition (DeWalle and Galeone 1990). Because current understanding of this threat is limited, mitigation is difficult, and impacts can persist for several years (Adams 2011), the impact of wastewater application is a medium-high research priority (Table 1).

◼ Conclusion

As the development of shale energy reserves continues to expand, substantial knowledge gaps remain regarding effects of these activities on plants and animals. Using criteria related to the environmental risks and current understanding of these impacts, we suggest that top research priorities are related to probabilistic events that lead to contamination of fresh water, such as equipment failure, illegal activities, accidents, chemical migration, and wastewater escape, as well as cumulative ecological impacts of shale development (Table 1). Although other threats are considered lower priorities, these rankings are relative, general, and dependent on the scarce peer-reviewed literature pertaining directly to shale development (WebTable 1). Certain components of relatively low-ranking threats (eg winter O_3, air pollution) may warrant greater prioritization, especially in particular regions or ecosystems. Furthermore, these rankings are based on the assumption that feasibility of mitigation translates to effective mitigation. For example, water scarcity has documented negative effects on aquatic organisms, and can be avoided by managing water withdrawals. Nevertheless, water management continues to be a major conservation issue in water-limited ecosystems. When the ecological consequences of shale development are easily foreseeable (ie deterministic), research focused on mitigation is generally a higher priority than determining basic effects on biota. In other cases (eg land application of wastewater), the need for research may be circumvented by a change in state or federal regulation.

Given the rapid expansion of shale development, the scientific community should prioritize research to examine threats with the greatest potential for biotic harm. Here, we identify four high-priority research areas, but acknowledge that these priorities are likely to change as scientific understanding, government regulations, and mitigation strategies develop. Rather than a rigid guideline, the approach presented here is a call to action for scientists, industry leaders, and decision makers. We must actively cooperate to understand the ecological risks associated with shale energy development and work to minimize its impacts on natural systems.

◼ Acknowledgements

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