Impacts of Shale Gas Development on Bat Populations in the Northeastern United States

Indiana bat (*Myotis sodalis*). Photo credit: Bat Conservation International.

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BACKGROUND

Natural gas development from shale is rapidly expanding across the US (Ground Water Protection Council GWPC and ALL Consulting 2009). Shale gas reservoirs, or plays, are distributed across the country (Fig 1.) and can be found at depths ranging from 152–4,115 meters (m). The most productive plays include the Barnett, Haynesville, Fayetteville, Woodford and Marcellus Shales (Zoback et al. 2010). In the northeastern US, the Devonian, Marcellus, and Utica shales extend across several states and are located within the Appalachian Basin Province (Coleman et al. 2011).

Figure 1. Location and size of shale gas reservoirs, or plays, in the United States. Source: US Energy Information Administration (USEIA) based on published data.

The process of producing natural gas from shale and other unconventional reservoirs (i.e., formations with low permeability and porosity) requires fracturing the rock formation. In high-volume hydraulic fracturing (HVHF) operations, highly pressurized fluid, consisting of water and various chemicals, is used to create these fractures. Suspended in the fluid is a propping agent, typically sand, which maintains the openings and allows gas to migrate to the well (Carter et al. 1996, Entrekin et al. 2011). To increase the volume of rock accessed by a single vertical well, operators rotate the drill and bore horizontally through the shale bed. Up to fifteen separate HVHF operations are possible per well (Kargbo et al. 2010).

OBJECTIVES

Concerns regarding the potential impacts to humans and the environment have grown in conjunction with the rapid expansion of shale gas development. Issues regarding water withdrawal, water contamination, habitat loss and degradation, impacts to terrestrial and aquatic ecosystems, and greenhouse gas (GHG) emissions surround HVHF operations. Moreover, no data exist on the possible adverse influence these operations have on bat populations. Because of recent concerns regarding rapidly declining bat populations in the northeastern US, there is increasing concern about the additive effects HVHF operations could have on already imperiled bat species. This report will focus on the environmental effects associated with shale gas development and the potential impacts to bat populations in the region.

ENVIRONMENTAL IMPACTS

Water withdrawal. The HVHF process requires large volumes of water per well to fracture shale formations. Estimates ranging from 2 to 7 million gallons of water are used per operation, depending on conditions of the site (NYDEC 2011, Susquehanna River Basin Commission [SRBC] 2010, US Environmental Protection Agency [USEPA] 2011). In 2006, the estimated 35,000 fractured wells across the US used between 70–140 billion gallons of water, equivalent to the total amount withdrawn from drinking resources each year by 40–80 cities with populations of 50,000 people, or 1–2 cities of 2.5 million people (Halliburton 2008, USEPA 2011). Source water comes from either surface (e.g., streams or lakes) or ground water (e.g., aquifers). Water can be withdrawn from a nearby source or transported by trucks or a pipeline, and stored on-site by large tanks or impoundments (GWPC and ALL Consulting 2009). Because ground and surface water are hydraulically connected, changes in the quantity and quality to one likely influence the other (Winter et al. 1998).

In the northeastern US, shale formations (e.g., Devonian, Marcellus, and Utica) underlie a number of sensitive watersheds, such as the upper Delaware River, a designated Wild and Scenic River that supplies drinking water to >15 million people. Stakeholder concerns include the high rate of water removal from small streams at the headwaters of these watersheds (Maclin et al. 2009, Myers 2009). Withdrawals of large quantities of water at these locations can significantly affect the hydrology and hydrodynamics of surface water resources. Changes in water depth can alter the flow regime, velocity, and temperature of springs, streams and lakes, affecting *in situ* flora and fauna (Zorn et al. 2008). Additionally, removal of significant volumes of water can reduce the dilution effect and increase the concentration of contaminants in surface water (Pennsylvania State University 2010).

Ground water resources (e.g., aquifers) also are tapped for HVHF operations. Rapid withdrawal from aquifers can lower the water table levels, changing water quality by exposing naturally occurring minerals to an oxygen-rich environment, potentially causing chemical changes that alter mineral solubility and mobility, leading to salination of water and other chemical contaminations. Lower water tables also may cause upwelling of lower quality water and other substances (e.g., methane) from deeper within an aquifer and could lead to subsidence or destabilization of the local geology. (USEPA 2011)

Water contamination and toxic exposures. In addition to water, HVHF fluids typically include a combination of additives that serve as friction reducers, cross-linkers, breakers, surfactants, biocides, pH adjusters, scale inhibitors, and gelling agents (New York State Department of Environmental Conservation [NYSDEC] 2010). The goal is to achieve an ideal viscosity that encourages fracturing of the shale and improves gas flow, while discouraging microbial growth and corrosion which can inhibit recovery efficiency (US Department of Energy [USDOE] 2009). The percentage of chemical additives in a typical HVHF operation is <0.5% by volume but can reach as high as 2% by volume (Soeder and Kappel 2009, NYSDEC 2011). Thus, an HVHF operation using 5 million gallons of water can use 25,000 to 100,000 gallons of chemical additives. The types and concentrations of chemical additive and proppants vary depending on conditions of the specific well being fractured, and companies typically create fracturing fluid tailored to the specifics of the formation and needs of the project (USEPA 2011). The New York State Department of Conservation (2011) lists chemicals proposed for use in the state by shale gas developers, including 235 products in hydraulic fracturing fluids, containing 322 unique chemicals and at least 21 additional compounds.

In 2011, the US House of Representatives Committee on Energy and Commerce launched an investigation examining HVHF practices. The Committee found that "between 2005 and 2009, 14 oil and gas service companies used more than 2,500 additives, containing 750 chemicals and other components", including "29 chemicals that are: (1) known or possible human carcinogens; (2) regulated under the Safe Drinking Water Act for their risks to human health; or (3) listed as hazardous air pollutants under the Clean Air Act" (Waxman 2011). The Committee revealed that over the 4-year period these additives included lead, ethylene glycol, benzene, toluene, and xylene compounds. Moreover, the investigation reported that over 32 million gallons of diesel fuel, one of the only additives regulated by the Safe Drinking Water Act, were injected across nineteen states.

Wastewater is generated during the HVHF process in the form of flowback (i.e., fluid returned to the surface after HVHF has occurred, but before the well is placed into production) and produced water (i.e., the fluid returned after the well is placed into production) (USEPA 2011). During injection, HVHF fluids come in contact with the bedrock, often affecting the mobility of naturally occurring substances in the subsurface, particularly in the hydrocarbon-containing formation. These substances include formation fluids (e.g., brine or sodium chloride; Piggot and Elsworth 1996), gases (e.g., methane, ethane, carbon dioxide, hydrogen sulfide; Zoback et al. 2010), trace elements (e.g., mercury, lead, arsenic; Harper 2008, Leventhal and Hosterman 1982, Tuttle et al. 2009, Vejahati et al. 2010), naturally occurring radioactive material (e.g., radium, thorium, uranium: Leventhal and Hosterman 1982, Harper 2008, Tuttle et al. 2009, Vejahati et al. 2010) and organic material (e.g., acids, polycyclic aromatic hydrocarbons, benzene, toluene, xylene; URS Corporation 2009, NYSDEC 2011). Some of these substances may be liberated from the formation via complex biogeochemical reactions with the chemical additives found in hydraulic fracturing fluid (Long and Angino 1982, Falk et al. 2006). New York tested flowback from Marcellus Shale gas production in Pennsylvania and West Virginia and found 154 chemicals, many of which are health hazards and are regulated via primary and secondary drinking water standards (NYSDEC 2011). A list of chemicals identified in flowback and produce water is presented in USEPA (2011; Table E2).

Estimates for recovery of fracturing fluid in flowback for the Marcellus Shale range from 10–30% (Arthur et al. 2008). The physical and chemical properties of wastewater vary with fracturing fluid, geographic location, geology and time (Veil et al. 2004, Zielinski and Budahn 2007, Zoback et al. 2010, Rowan et al. 2011). During or prior to treatment, flowback and produced water often are retained on-site in storage tanks, open-air impoundments or evaporation ponds (GWPC and ALL Corporation 2009). Later, these fluids are transported to treatment facilities, injected underground, or discharged to waterways and the environment. Underground injection is the primary method of wastewater disposal from all major plays, except for the Marcellus Shale (Horn 2009, Veil 2007, 2010). For some operations, fluids are transported to wastewater treatment at publicly-owned treatment works or commercial wastewater treatment facilities. However, few facilities are capable of treating fluids containing dangerous contaminants (e.g., radioactive materials), brine (high salinity fluids), and unique compounds, which often are expensive to remove, generated by HVHF operations (Veil 2010, US General Accounting Office [USGAO] 2012).

Contamination from wastewater can occur at any time during operations. Large HVHF operations require extensive quantities of supplies, equipment, and vehicles, which may increase the risks of accidental releases, such as spills or leaks. Surface spills or releases can occur as a result of tank ruptures, impoundment failures, overfills, vandalism, accidents, or improper operations. Released fluids also may flow into nearby surface water bodies or infiltrate into the soil and near-surface groundwater (NYSDEC 2011). Entrekin et al. (2011) reported that 80% of Marcellus Shale gas wells are located within 200 m of riparian areas and 100% are within 300 m. Regulating the rapid expansion of HVHF operations is problematic and violations are common (Entrekin et al. 2011). For example, between January 2008 and December 2011 a total of 3,355 violations of environmental laws by 64 different Marcellus Shale gas drilling companies were reported by the Pennsylvania Department of Environmental Protection. Of these, 2,392 violations of these that likely posed a direct threat to our environment and were not reporting or paperwork violations (Staaf 2012).

The ability of naturally occurring but toxic substances or fracturing fluids to reach ground or surface waters is possible if fractures extend beyond the target formation and reach aquifers, or the casing or cement around wells fails causing contaminants to migrate into drinking water (USEPA 2011). Contamination also can occur through mismanagement and improper operating procedures, inadequate waste treatment practices, improper storage, or inadequately constructed impoundments or well casings. Occurrences of improper well construction and operation, allowing subsurface pathways for contaminant migration resulting in water pollution have been reported (State of Colorado Oil and Gas Conservation Commission 2009a, b, c, PADEP 2010, USAEPA 2010, McMahon et al. 2011). A study in the Marcellus Shale region concluded that methane gas was seventeen times higher in water wells closer to natural gas wells. (Osborne et al. 2011). The concentration of methane in these wells fell within the defined action level for hazard mitigation recommended by the US Office of the Interior (Eltschlager et al. 2001).

Sub-lethal impacts of shale gas development also may adversely influence aquatic environments and interfere with ecological interactions, such as whole-stream metabolism, decomposition of organic matter and accrual of macro-invertebrate biomass (Evans-White and Lamerti 2009). Land clearing during well pad and infrastructure (e.g., roads and pipelines) development, and increased road traffic throughout operations can increase sediment runoff into adjacent streams, lakes and wetlands (Williams et al. 2008, Entrekin et al. 2011). Excessive sediment in aquatic habitats results in higher levels of suspended and benthic particles, which may reduce stream flow, alter light, temperature, dissolved oxygen, and pH levels, and degrade spawning habitat for macro-invertebrate insects (Wood and Armitage 1999, Williams et al. 2008). Reductions in feeding efficiencies or the availability and abundance of prey can lead to negative effects on reproduction and growth of higher trophic-level animals (Peckarsky 1984, Sandheinrich and Atchison 1989, Burkhead and Jelks 2001). Moreover the introduction of chemicals associated with shale gas development (i.e., HVHF fluids and wastewater) can lead to a decline in production by eliminating sensitive taxa representing a majority of community growth and or biomass (Woodcock and Huryn 2007).

Habitat loss and degradation. Habitat loss or degradation is commonly associated with anthropogenic activities, including those of the oil and gas industry. Historically, with vertical drilling, one well pad equaled one well, but horizontal drilling allows for multiple wells per well pad (GWPC and ALL Consulting 2009). However, with the rapid expansion of this energy sector, hundreds of thousands of well sites are projected over the next twenty years, many of which are slated for forest habitat. For Marcellus Shale operations in Pennsylvania, an average, 8.8 acres (3.6 hectares [ha]) of habitat are required for each well pad and associated infrastructure (e.g., storage areas, roads and pipeline corridors) (Johnson 2010). The cumulative impact of all operations in a region can result in landscape level changes in habitat. For example, the projected number of wells by 2030 in Pennsylvania alone ranges from 6,000 to 15,000 (Johnson 2010). Given that nearly two thirds of these wells are expected to occur on forest lands, the potential area of forest to be cleared varies from 33,800 acres (13,800 ha) to 83,000 acres (32,700 ha). Additional habitat loss is likely as other formations, such as the Utica Shale, are developed.

Damage to forest habitat can occur from mechanical clearing during site development and from mismanagement of wastewater. At the US Forest Service Fernow Experimental Forest, damage to over two dozen trees and ground vegetation adjacent to a well pad occurred when HF fluid escaped the well bore during drilling (Adams et al. 2011). The release of fluid drifted over the immediate area causing browning of foliage and loss of leaves and ground vegetation. A major component of the HF fluid, and likely cause of damage, at this site was hydrochloric acid (15% by volume). Subsequent to this accident, fluids were experimentally applied to forest patches. Temporal and spatial development of the applications suggested that direct contact and uptake from the soil by the roots resulted in detrimental effects. A total of 147 trees (11 species) were affected. The application resulted in a much more open canopy than either control or recently burned plots, resulting in significantly more light penetration.

Removal of forest habitat, regardless of method, creates an associated edge effect ranging from 100–300 m into the interior forest stand. Increasing light and wind exposure, and changing temperature can alter vegetation dynamics, causing avoidance by many birds, mammals, reptiles and amphibians (Gibbs 1998, Flashpohler et al. 2001, Marsh and Beckman 2004). Disturbed areas also are more vulnerable to invasive plants (Meeking and McCarthy 2001, Harper et al. 2005). Furthermore, the distribution of clearings will increase forest fragmentation, resulting in species isolation and loss of genetic diversity (Lee et al. 2011). In Pennsylvania, Johnson (2010) estimated an additional 21 acres (8.6 ha) of interior forest habitat would be affected for every 8.8 acres (3.6 ha) of cleared forest for Marcellus Shale development. Thus, a total of direct and indirect impacts to forest habitat could equal 30 acres (12.3 ha) per well pad, resulting in 81,500 to 200,300 acres (33,340–81,940 ha) of forest habitat loss or degradation (Johnson 2010). Drohan et al. (2012) indicated this level of impact was enough to substantially alter the Pennsylvania landscape.

Greenhouse gas emissions. During combustion, natural gas emits less carbon dioxide (a greenhouse gas [GHG]), nitrogen oxide and sulfur oxide (two contaminants contributing to acid rain) than coal (Entrekin et al. 2011). However, during extraction, shale gas development produces considerable amounts of methane, a major component of natural gas and a powerful GHG (Howarth et al. 2011). The amount of fugitive emissions of methane into the atmosphere during HVHF operations compared to conventional operations may contribute more to global warming than other fossil fuel development (USEPA 2010). Howarth et al. (2011) calculate that during the life cycle of an average shale gas well, 3.6–7.9% of the total production of the well is emitted to the atmosphere as methane, which is at least 30% to 50% as great as estimated for a conventional well. Methane dominates the GHG footprint for shale gas on a 20-yr time horizon, contributing 1.4–3 times more than does carbon dioxide emission, resulting in a GHG footprint for shale gas at 22%–43% greater than that for conventional gas.

POTENTIAL IMPACTS TO BATS

Bats of the northeastern US are insectivorous and are the primary consumers of nocturnal arthropods, including many agricultural and forest pests. Given the relatively large volumes of insects consumed (up to 100% of bats body mass/night; Kurta et al. 1989) and extensive foraging home ranges, bats play a major role in suppressing nocturnal insect populations and transporting nutrients across landscapes (Fenton 2003, Jones et al. 2009). Moreover, bats provide an economic benefit by saving US farmers an estimated $22.9 billion (range: $3.7–$53 billion) each year in pesticide use (Boyles et al. 2011). Because of their important role in ecosystem services, bats often are used as indicators of habitat quality (Wickramasinghe et al. 2003, Kalcounis-Rupell et al. 2007, Jones et al. 2009). Bats may serve as the proverbial “canary in the coalmine” because many of their life history traits make them sensitive to human-induced environmental changes (Estrada et al. 1993, Medellin et al. 2000, Moreno and Halffler 2000, 2001, Estrada and Coates-Estrada 2001a, b, Clarke et al. 2005a, b, Hayes and Loeb 2007, Kunz et al. 2007). Bats have low reproductive potential (i.e., reproducing once per year and typically only having a single pup) and require high adult survivorship to avoid population declines (Barclay and Harder 2003, Podlutsky et al. 2005). Because bats are not able to recover quickly, large-scale changes may put populations at risk (Findley 1993, Henderson et al. 2008).

Historically, contamination from pesticide use and loss or disturbance of suitable habitat contributed to population declines. In recent years, both anthropogenic and natural forces have adversely affected North American bats, particularly in the northeast. Since 2003, wind energy development has resulted in potentially hundreds of thousands of bat fatalities (Kunz et al. 2007, Arnett et al. 2008). Although wind-powered turbines primarily affect migratory tree-roosting bats, cave-roosting species (e.g., little brown bat [*Myotis lucifugus*] and tri-colored bat [*Perimyotis subflavus*]) can compose approximately 20% of fatalities (Arnett et al. 2008). In 2006, the first fatalities from White-nose Syndrome (WNS) were documented in New York. Over the past six years, the fungus (*Geomyces destructans)* causing WNS has spread across nineteen states and killed millions of bats from six different species (Bat Conservation International; www.batcon.org). Little brown bats, once considered common, have shown the greatest mortality of all species affected by WNS (Frick et al. 2010b), but northern long-eared (*M. septentrionalis*), eastern small-footed (*M. leibii*), Indiana (*M. sodalis*), and tricolored bats also have experienced severe mortality (Kunz and Reichard 2011). Turner et al. (2011) estimated an 88% decrease in the total number of hibernating bats, with 98%, 91% and 72% declines in hibernating northern long-eared, little brown bats, and Indiana bats, respectively.

The perilous decline in bat populations is exacerbated by the additive nature of both WNS and numerous anthropogenic activities, possibly including shale gas development (USGS 2009). Coincidentally, the Marcellus Shale lies within the same area as the epicenter of WNS. The impacts associated with natural gas exploration and extraction in this region may further imperil already decimated bat populations (Matteson 2010). Of particular concern are the Indiana bat, currently listed under the Endangered Species Act, the northern long-eared and eastern small-footed, recently petitioned for listing by the Center for Biological Diversity (Matteson 2010), and the little brown bat, a species predicted to be extirpated from a significant proportion of its range by 2026 (Frick et al. 2010b, Kunz and Reichard 2011). Although there are no publicly available studies investigating the impacts of shale gas development on bats, we can infer potentially adverse effects based on other human-induced landscape-level changes.

Water withdrawal. Aquatic habitats play a critical role in the ecology of bats, both as sources of water and insect prey (Racey and Swift 1985, Grindal et al. 1999, Downs and Racey 2006, Hayes and Loeb 2007). Bats have relatively high rates of evaporative water loss, and must obtain much of their intake from available surface water resources (Kurta et al. 1989, 1990, McClean and Speakman 1999, Webb 1995, Neuweiler 2000). Kurta et al. (1989) estimated that bats may drink up to 26% of their daily water intake from open water sources (e.g., ponds or streams) to maintain water balance. Available water is vital for reproductively active females, particularly lactating bats, which require a sufficient amount of water while nursing young (Johnson et al. 2011). Adams and Hayes (2008) observed lactating female bats drinking 13 times more often than non-reproductive bats. Moreover, studies have shown that pregnant and lactating female bats select foraging areas, in part, based on proximity to water (Speakman et al.1991, McClean and Speakman 1999, Adams and Thibault 2006). For example, Johnson et al. (2011) observed eastern small-footed bat roosts within 500 m from water sources.

Riparian areas and other hydric habitats (e.g., lakes, ponds, and wetlands) are important resources because they support higher concentrations of nocturnal insects (MacGregor and Kiser 1998). Many bat species are opportunistic foragers and select areas where abundant and available prey occur (Thomas 1988, Barclay 1991, Barclay and Brigham 1991, Hart et al. 1993, Krusic and Neefus 1996, Grindal et al. 1999, Broders 2003). Murray and Kurta (2002) found that aquatic insects compose a large proportion of the diets of Indiana bats in the northern part of the species range. Commuting and foraging activity for many species is typically higher in riparian areas than in upland sites (Furlonger et al. 1987, Krusic et al. 1996, Grindal et al. 1999, Zimmerman and Glanz 2000, Seidman and Zabel 2001, Veilleux et al. 2003, Leput 2004, Menzel et al. 2005) and some species spend significant proportions of their nightly activity in these areas (LaVal et al. 1977, Brigham et al. 1992, Barclay 1999, Fellars and Pierson 2001, Waldien and Hayes 2001). Thus, the extensive withdrawal of water resources from the environment, particularly in sensitive areas or areas under drought conditions, will presumably affect roost-site selection and abundance and availability of prey.

Water contamination and toxic exposures. Riparian habitats support large numbers of insects and are prime foraging areas for insectivorous bats (Vaughn et al. 1996,). However, the inflow of heavy metals and other toxins from industrial wastes can adversely affect water quality and the invertebrate community (Mason 1997, Jones et al. 2009). Bats have been observed congregating and drinking from holding ponds at industrial sites (Huie 2002). Clark and Hothem (1991) reported the occurrence of bats dying by asphyxiation after drinking solutions containing cyanide from open holding ponds of gold mining operations. Similarly, open pits containing flowback and produced water associated with HVHF operations could expose bats to toxins, radioactive material and other contaminants.

Exposure to environmental contaminants is a suspected factor in the decline of North American bat species (US Fish and Wildlife Service [USFWS] 1999, Schmidt et al. 2002). Metabolic processes of insectivorous bats are rapid and bats consume large quantities of food relative to their body mass (Kurta et al. 1989, Schmidt et al. 2002). Because dietary accumulation and metabolic capacity increase at higher trophic levels, and because insectivorous bats are apex predators, bats are likely more susceptible to contaminants (Allerya et al. 2000, Eisler and Wiemeyer 2004, Jones et al. 2009). Toxic contamination can occur during normal operations, accidentally or by improper management. In such an event, contaminated drilling mud or water may migrate into caves and fissures used by bats, which can be ingested by grooming or be inhaled (Adams et al. 2011). Toxins often accumulate in fat, and are more likely to have adverse physiological effects when bats are depleting fat reserves, such as during hibernation, migration, or lactation (Kurta et al. 1989, O'Shea and Clark 2002).

Three heavy metals, cadmium, mercury, and lead, commonly associated toxins in wildlife studies, are contaminants reported in HVHF operations. Cadmium affects a number of systems, including reproductive and renal systems (Chmielnicka et al. 1989, Walker et al. 2007). A paucity of information exists on the occurrence and affect on cadmium in bats. However, Clark et al. (1988) postulated a relationship between cadmium concentrations in the guano of grey bats (*M. grisescens*), a federally endangered species, and kidney lesions. Mercury concentrations in aquatic and terrestrial food webs of the northeastern US are considered detrimental to local bat populations (Driscoll 2007, Osborne et al. 2011). Observed consequences of mercury exposure in mammals include reduced immune function, hormonal changes, impaired function of the central nervous system and motor skill impairment, and reduced reproductive success (Wiener and Spry 1996, Nocera and Taylor 1998, Evers et al. 2004, Schweiger et al. 2006). Lead is the most ubiquitous toxic metal and has been associated with a wide range of toxic effects from neurological, hematological, renal, and reproductive (Goyer 1996). Several studies have reported the potential negative impacts of lead on both wild and captive bats (Zook et al. 1970, Sutton and Wilson 1983, Hariono et al. 1993, Skerratt et al. 1998, Walker et al. 2007), including a possible link between elevated concentrations of lead and still births in big brown and little brown bats (Clark 1979).

Data on the impacts of other toxins and radionuclides on bats is limited (Eisher 1994, Ma and Talmage 2001, O'Shea and Clark 2002). The majority of data on bats and environmental contaminants comes from studies investigating the impacts of pesticides, and, to a lesser extent, heavy metals (O'Shea and Clark 2002, Schmidt et al. 2002). However, if contaminants associated with HVHF operations are introduced into aquatic ecosystems and are readily transferrable through insectivorous food chains, bats will presumably accumulate these substances and potentially suffer adverse effects.

Habitat loss and degradation. Fragmentation is considered a primary threat to global biodiversity (Franklin et al. 2002) and has the potential to directly impact bat populations by limiting essential roosting and foraging resources (Fenton 2003, Safi and Kerth 2004, Lane et al. 2006, Henderson et al. 2008). Anthropogenic changes in ecosystems often result in fragmenting forest landscapes and typically occur at rates dramatically faster than long-lived organisms are capable of adapting, thus disrupting life history cycles and ecological processes (Duchamp and Swihart 2008). Rapid ecosystem changes are associated with population declines in many bat species (Jones et al. 2009, Safi and Kerth 2004). In North America, the result of human-induced changes often results in patchy species distributions rather than range contraction (Pierson 1998). Recent studies have focused on temperate bat communities in greatly modified ecosystems, finding a positive association between bat abundance and diversity, and remnant natural habitat, such as forests and wetlands (Walsh and Harris 1996, Jaberg and Guisan 2001, Russ and

Montgomery 2002, Gehrt and Chelsvig 2004, Duchamp and Swihart 2008). Negative effects on bats from forest cover loss also are well documented from processes such as forest harvesting (Grindal 1996, Patriquin and Barclay 2003) urban expansion (Evelyn et al. 2003, Duchamp et al. 2004, Sparkes et al. 2005a) and agricultural intensification (Russ and Montgomery 2002, Lesinski et al. 2007).

Intact, mature forest stands possess structural features such as snags and large, overstory trees that are vital for cavity- and foliage-roosting bats, respectively (Jung et al. 1999, Cryan et al. 2001, Carter and Feldhamer 2005, Broders et al. 2006, Perry and Thill 2007, O'Keefe et al. 2009). In summer, bats select specific structures that offer protection and appropriate thermoregulatory conditions for survival and development of young (Humphrey et al. 1977). Loss of forest cover and degradation of forested habitats have been cited as part of the decline of Indiana bats (USFWS 1983, Gardner et al. 1990, Garner and Gardner 1992, Drobney and Clawson 1995, Whitaker and Brack 2002). Presence of northern long-eared bats, an interior forest species, is dependent on mature, contiguous deciduous forests for both roosting and foraging habitat (Sasse and Perkins 1996, Hutchinson and Lacki 2000, Lacki and Schwierhojan 2001, Broders and Forbes 2004, Carter and Feldhamer 2005, Broders et al. 2006, Perry et al. 2007, Henderson and Broders 2008). Moreover, this species forages almost exclusively in closed canopy forests and avoids forest gaps and open areas (Owen et al. 2003, Patriquin and Barclay 2003, Schirmacher et al. 2009).

Many forest-dwelling bats frequently switch roosts (Lewis 1995), but tend to remain loyal to specific roosting and foraging areas. Site fidelity is advantageous, allowing bats to become familiar with suitable roost trees and the local spatio-temporal variation in prey abundance and availability, thus decreasing time spent commuting and foraging (Avital and Jablonka 2000, Broders et al. 2006). Studies of Indiana bat roost-site selection show reproductively active females returning to the same home range year after year to establish maternity colonies. (Humphrey et al. 1977, Gardner et al. 1991a, 1991b, Gardner et al. 1996, Callahan et al. 1997, Menzel et al. 2001, Kurta and Murray 2002, Britzke et al. 2003, Whitaker and Sparks 2003, Whitaker et al. 2004). Roost tree reoccupation of up to six years has been documented in a number of studies (Garner et al. 1991b, Whitaker et al. 2004, Barclay and Kurta 2007). Maternity colonies of Indiana bats also appear to be faithful to their foraging areas within and between years (Cope et al. 1974, Humphrey et al. 1977, Gardner et al. 1991a, 1991b, Murray and Kurta 2004, Sparks et al. 2005b). Similarly, northeastern long-eared, eastern small-footed, and tri-colored bats select specific areas, often re-using sites within and among years (Kalcounis and Hecker 1996, Sasse and Pekins 1996, Brigham et al. 1997, O'Donnell and Sedgley 1999, Weller and Zabel 2001, Menzel et al. 2002, Willis and Brigham 2004, Perry and Thill 2007).

The philopatry observed among numerous species requires consideration by natural resource managers who often permit harvesting trees during winter when bats are hibernating, a practice intended to limit directly harmful effects of development (Arnold 2007). However, because females consistently return to the same site(s), this practice may do less to mitigate the immediate effects of habitat loss than anticipated. Bats, already pregnant, arrive to sites after hibernating for seven months and migrating for up to 500 kilometers (km), at a time of cool, wet weather, which likely limits prey availability (Humphrey et al. 1977, Kurta et al. 1996, Murray 1999). The loss or alteration of forest habitat places additional stress on females, and may increase thermoregulatory costs and potentially disrupt social bonds of a colony (Kurta and Murray 2002). Such impacts have been documented in other bat species. Brigham and Fenton (1986) documented a 56% decline in reproductive success of a big brown bat colony that was excluded from their maternity roost. Sparks et al. (2003), demonstrated that the natural loss of a single primary maternity roost lead to fragmentation of the colony (bats used more roosts and congregated less) the following year after roost loss.

Hibernacula and the habitat surrounding these sites also warrant protection from development, particularly drilling operations. Hibernating bats select sites within caves and mines possessing specific microclimate (e.g., temperature, humidity, and airflow) conditions (Clawson et al. 1980, Tuttle and Kennedy 2002). Alterations to this microclimate, whether natural or human-induced, often render a site less suitable for hibernation (Johnson et al. 2002). Moreover, disturbing bats during winter hibernation may result in additional arousals causing bats to lose fat reserves and possibly abandon the roost. Adams et al. (2011) highlighted the importance of understanding the connectivity of karst geology in proximity to winter hibernacula prior to development. Modifications to the surface habitat surrounding hibernacula also can contribute to changes in microclimate conditions, as well as influence the suitability of foraging characteristics. The landscape surrounding hibernacula supports foraging and roosting needs of large numbers of bats during fall swarming periods, when bats are building up crucial fat reserves to survive the winter (Hall 1962). Areas surrounding hibernacula also provide important summer habitat for male Indiana bats that do not migrate far from the winter roost.

Habitat use by forest bats is complex and varies by species. Bats rely on extensive resources over large areas (Duchamp et al. 2009). The magnitude of shale gas development predicted over the next twenty years is expected to have similar effects on forest landscapes (i.e., habitat loss and degradations) as other anthropogenic activities, but at a much greater level due to the proliferation of projected drilling sites. Therefore, providing conditions necessary to support bat populations will require a combination of designating certain forest areas as off-limits and implementing forest management practices that perpetuate suitable roosting and foraging habitat (Duchamp et al. 2009).

Greenhouse gas emissions. The effects of climate change on bats have not been studied extensively. However, it is believed that insectivorous bats may be among the most affected species because seasonal temperature changes may affect hibernation, food abundance and availability, and recruitment (Jones et al. 2009). Most bat species have specific temperature regimes that are conducive for surviving over half the year in hibernation. For example, Indiana bats hibernate in caves or mines where the ambient temperature is consistently below 10° C (Hall 1962, Meyers 1964, Henshaw 1965, Humphrey 1978, Tuttle and Kennedy 2002). Tuttle and

Kennedy (2002) reported that populations hibernating with temperatures between 3–7.2° C remained stable or increased, whereas populations hibernating at temperatures above or below this range were unstable or declined. With winter conditions expected to become shorter and warmer, disruptions to the mammalian overwintering energy budgets are expected (Gu et al. 2008). Milder winter conditions may force bats to enter hibernacula later than usual, presumably with inadequate fat reserves if food availability decreases in late fall (Matteson 2010). Warmer temperatures in winter also may result in unsustainable arousal frequencies (Humphries et al. 2002). Because arousals account for up to 80% of the energy budget (Thomas 1995) of hibernating bats, any increase in frequency or duration could decrease survivorship.

It has also been posited that changes in temperature may disrupt bat reproductive physiology. In winter, altered temperature regimes may diminish the viability of spermatozoa stored in the female reproductive tract, thus females may not become pregnant upon emergence, or become pregnant too early and undergo embryonic development and parturition earlier in the spring, which may lead to declining recruitment if conditions are not suitable for young (Jones et al. 2009). In summer, dwindling water resources caused by warmer temperatures and reduced precipitation can lead to lower reproductive rates as female are not able to meet their water budget to produce milk for nursing pups (Kurta and Rice 2002, Barclay et al. 2004, Adams and Hayes 2008, Rodenhouse et al. 2009). Adams (2010) observed reductions in reproductive behavior and increases in non-reproductive female bats in years with above average temperature and below average precipitation, conditions similar to predictions of regional climate warming and increased drought.

Changes in precipitation and temperature also are anticipated, thus diminishing water availability during summer and altering the distribution, abundance, and phenology of insects (Hughes 2000, Bale et al. 2002, Parmesan 2003, Menendez 2007, Rodenhouse et al. 2009). Reductions in insect abundance and availability will have detrimental effects on bat populations, particularly during critical periods (i.e., during pregnancy, lactation and fall swarming). Frick et al. (2010a) concluded a direct relationship between cumulative summer precipitation and probability of survivorship in little brown bats.

Climate data indicates we are in a rapid period of change, which already is being observed across a range of ecosystems (Jones et al. 2009). Climate change is likely to affect roosting and foraging behaviors and opportunities, particularly during times when bats are most vulnerable. Anthropogenic activities that increase the global GHG footprint, including HVHF operations, presumably will exacerbate adverse impacts on bat populations. Thus, methods to reduce the fugitive emissions of methane from shale gas development should be explored and implemented.

CONCLUSIONS

Bats are vital in terms of their ecological and economic roles, and are well suited as indicators of environmental health (Fenton 2003, Jones et al. 2009). Worldwide, bats function as pollinators, seed dispersers, and biological controls for nocturnal insects (Kunz and Parsons 2009). In North America, most species are insectivorous and consume large quantities of night-flying insects, many of which are agricultural and forest pests. Regrettably, many bat species are experiencing population declines and range contraction in response to both natural and human-induced environmental stressors (Jones et al. 2009). White-nose Syndrome has decimated hibernating bat populations in northeastern North America, including declines of nearly 98% and 88% in Pennsylvania and New York, respectively (Turner et al. 2011). Species affected include the little brown bat, a once common species, and the federally endangered Indiana bat (Frick et al. 2010b). At least three additional species are being considered for listing (Matteson 2010 Kunz and Reichard 2011). A sense of urgency exists among bat biologists because bats have low reproductive rates and respond slowly to rapid population declines (Barclay and Harder 2005). Compounding the devastation of White-nose Syndrome are human activities associated with the degradation and destruction of suitable habitat and resources for these imperiled species (Kunz and Parsons 2009). As with other industrial practices, shale gas development contributes to water withdrawal and contamination, habitat loss and degradation, and the emission of GHGs resulting in detrimental effects on bat populations and their environment. Immediate action is required to reduce these adverse impacts and to ensure that bats and the ecosystems they serve are considered during shale gas development and production.

Eastern small-footed bat (*Myotis leibii*). Photo credit: Bat Conservation International.

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