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Risks to biodiversity from hydraulic fracturing for natural gas in the Marcellus and Utica shales

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High-volume horizontal hydraulic fracturing (HVHHF) for mining natural gas from the Marcellus and Utica shales is widespread in Pennsylvania and potentially throughout approximately 280,000 km^2 of the Appalachian Basin. Physical and chemical impacts of HVHHF include pollution by toxic synthetic chemicals, salt, and radionuclides, landscape fragmentation by wellpads, pipelines, and roads, alteration of stream and wetland hydrology, and increased truck traffic. Despite concerns about human health, there has been little study of the impacts on habitats and biota. Taxa and guilds potentially sensitive to HVHHF impacts include freshwater organisms (e.g., brook trout, freshwater mussels), fragmentation-sensitive biota (e.g., forest-interior breeding birds, forest orchids), and species with restricted geographic ranges (e.g., Wehrle's salamander, tongue-tied minnow). Impacts are potentially serious due to the rapid development of HVHHF over a large region.

Keywords: Appalachian Basin; biodiversity; forest fragmentation; hydraulic fracturing; salinization; shale gas

Introduction

High-volume horizontal hydraulic fracturing (HVHHF) occurs at increasing density across potentially 280,000 km^2 of the eastern United States underlain at depth by the natural gas–bearing Marcellus and Utica shales. These industrial installations and their edge effects alter as much as 80% of local landscapes.[1] The predicted intensity, speed, and extent of industrialization of the landscape have engendered concern about human health but little discussion of the effects on biodiversity,[2–4] although HVHHF has been identified as a global conservation issue.[5] Although the biota of the eastern United States is relatively well studied, many of the rare organisms potentially susceptible to industrial impacts are not. For example, the woodland salamanders (*Plethodon*) are diverse and sensitive to landscape and soil conditions; many species have only been described in recent decades; and as a group they are declining.[6–8] Although a direct survey of many taxa may be infeasible, indicator taxa may not effectively represent overall diversity.[9] In general, various taxa use different micro- and macrohabitats and have different conservation needs; one taxon may not predict the occurrence or sensitivity to impacts of another taxon.[10] This review focuses on the physical and chemical impacts of HVHHF on habitats, taxa, and guilds, and suggests which organisms have particular sensitivities that may put them at risk.

The Marcellus–Utica region

Conservatively, 9.5% of the conterminous United States is underlain by gas shales;[11] Canada, southern South America, Europe, South Africa, North Africa, China, India, and Australia also have exploitable formations.[12] The most extensive resources in the eastern United States are the Marcellus and Utica shales, underlying the Appalachian Basin from approximately the Mohawk and Hudson rivers in New York, through extensive areas of Pennsylvania and Ohio, most of West Virginia, and into small parts of Maryland, Virginia, and Ontario (Fig. 1).[13] Much of the region is forested, with dominant trees that include oaks (*Quercus* spp.), hickories (*Carya* spp.), sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), and yellow birch (*Betula allegheniensis*).[14] Elevations range

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Figure 1. Map of the Marcellus–Utica shale region. Reprinted with the permission of Cambridge University Press.[8]

from less than 100 m near the Hudson River to more than 1500 m in north-central Pennsylvania.

The Marcellus and Utica shales are organic-rich, marine shales deposited during the Middle Devonian and Middle Ordovician periods, respectively. The formations vary from exposed (in small areas) to overlain by 3 km or more of other bedrock strata, with the Utica underlying the Marcellus and extending farther west and southwest. Some of the organic matter is methane, the principal constituent of natural gas, tightly bound in microscopic pores.

Hydraulic fracturing

Horizontal drilling and hydraulic fracturing were developed in recent decades to mine gas from deep strata. In a typical installation, one to several wells are drilled from a single wellpad. Each well descends vertically 1.5 km or more to the target shale stratum, and then continues horizontally as much as 1.5 km. Fracturing fluid (water, chemicals, and sand) is forced under high pressure into the shale to open and prop spaces that let gas flow into the well.[13]

After fracturing, the gas and a portion of the fracturing fluid ascend the well and are collected. The gas is cleaned, compressed, and piped via collector lines to transmission pipelines.

Each HVHHF installation constitutes a wellpad, an access road, storage areas for water, chemicals, sand, and wastewater, a compressor station, and a collector pipeline. Installations often require extensive cut-and-fill, and some are on steep slopes.[15] In Pennsylvania in 2008, half of the installations were in forests and used, on average, 3.56 ha, thereby affecting approximately 15 ha of forest per installation.[1] An estimated 60,000 new wells will be in place by 2030.[16] A well is fractured at intervals of several years during its projected 40- to 50-year life, and each wellpad may support several wells. Each fracturing episode, per well, uses $4–12 \times 10^6$ L of water, which is usually trucked from a lake or river (the amount per episode may be as high as $15–25 \times 10^6$ L).[17] The portion of water and chemicals that returns to the surface as wastewater has been estimated at 9–100%.[18] More than 600 synthetic chemicals are used in HVHHF, including methanol, napthalene, xylene, acetic acid, ammonia, and #2 fuel oil,[2] but those used in any given well are unidentified. These chemicals constitute about 0.5% of the fracturing fluid; because of the large volume of fluids, 1×10^6 L of chemicals may be injected with a portion returning to the surface.[4,13] The wastewater, either return water during the fracturing operation or produced water afterward,[4] also contains substances from the shale, especially sodium, chloride, bromide, arsenic, barium, other heavy metals, organic compounds, and radionuclides.[13] Wastewater is often stored in lined, open ponds near wellpads, apparently to concentrate it, then trucked to treatment plants (including municipal plants not designed to remove salinity or radionuclides, and discharging effluent that has sometimes led to high salinity or total dissolved solids in rivers).[13,18] Wastewater is also reused for fracturing, disposed of by deep injection, spread on roads for dust control, or concentrated by evaporation and buried.[2,15,18]

Assessing biodiversity risk

Water and soil pollutants

Many spills or leaks of raw chemicals, fracturing fluids, or wastewater have been documented, involving volatile and gaseous organic chemicals, diesel fuel, surfactants, metals, sodium chloride, acidic water, and other substances.[2,3,19–21] In one instance, the median chloride content of wastewater was 56,900 mg L^{-1}.[18] At a West Virginia site, wastewater with approximately 4,000–14,000 mg L^{-1} chloride was sprayed on ground and vegetation, killing trees and other plants.[15] Four northeastern amphibian species have been shown to be adversely affected by approximately 50–1,000 mg L^{-1} chloride, depending on the species and life stage,[22] suggesting that small amounts of HVHHF wastewater could render breeding habitats unsuitable. Many lichens,[23–25] liverworts,[26] sphagnum mosses,[27–29] conifers,[30,31] aquatic plants,[32,33] and bog plants[34] are also sensitive to salt; numerous streams are already salinized from road deicing.[35] Furthermore, lichens[36–40] and stoneworts[41–43] can be harmed by heavy metals. Wastewater ponds contain highly toxic synthetic chemicals[2] and could potentially be ecological traps for water birds, muskrat, turtles, frogs, and aquatic insects. Mixtures of these chemicals will have effects that cannot be predicted by knowledge of individual chemicals.[3]

Sediment pollution of streams and other habitats may be caused by heavy equipment on rural roads mobilizing mineral particles in runoff or airborne dust,[13] or by inadequate erosion control at HVHHF sites.[21] In an HVHHF region of Arkansas, stream turbidity was correlated with well density.[3] Suspended sediment additions to higher order streams could potentially harm benthic invertebrates and fish; native brook trout and freshwater mussels are among the most vulnerable taxa. Dust from roads can harm nearby plants and pollute streams.[35]

Forest loss and fragmentation

Loss of forest cover and change in the spatial pattern of cover are often confounded, but cause different responses.[44] Edge effects on forest biota range from 10 m for trees to as much as 500 m for certain birds.[45] Forest fragmentation, which affects dispersal, pollination, herbivory, and predation, is a major conservation concern in HVHHF landscapes;[1,16,46] 20% or more of the forest cover may be removed for the establishment of HVHHF installations, and more than 80% of the land may be affected if a 100-m edge effect is considered.[1] This loss and fragmentation of forest would result in the warming and drying of the remaining forest, with greater penetration by nonnative plants, songbird nest predators, and the brood-parasitic brown-headed cowbird (*Molothrus ater*). Several forest amphibians occur at lower abundances in forest within 25–35 m of clearcut edges,[47] and juvenile forest amphibians have trouble dispersing across open habitats.[48,49] At five conventional gas well sites in West Virginia, three salamander species were more abundant closer to the forest edge, but less so in the drier southwestern aspect than in the moister northeastern aspect; edge effect was offset by rock and coarse woody debris (CWD) microhabitats.[50] Organisms sensitive to forest fragmentation include lichens and bryophytes,[51] orchids,[52] other herbs,[53] the West Virginia white butterfly (*Pieris virginiensis*),[54] amphibians,[8,48,55] and birds.[56–59] Orchids are among the taxa most sensitive to habitat change in that many orchid species occur in small, isolated populations and depend on narrow ranges of soil moisture, organic matter, light, and nutrients; they also have complex obligate relationships with mycorrhizal fungi and pollinators.[60] In addition, drying of air and soils near forest edges can degrade habitat for certain grape ferns (*Botrychium*).[61]

Pennsylvania forests serve as habitat reserves for many species.[46] Forest fragmentation and loss threaten populations of several breeding birds of conservation concern in Pennsylvania and West Virginia, including wood thrush (*Hylocichla mustelina*), cerulean warbler (*Setophaga cerulea*), and summer tanager (*Piranga rubra*).[62–64] Concern has been raised about potential HVHHF impacts on breeding populations of area-sensitive forest interior songbirds, such as black-throated blue warbler (*Setophaga caerulescens*) and a wide-ranging forest raptor, the northern goshawk (*Accipiter gentilis*).[1] In a 5-year study of breeding birds at 469 sampling points in forest patches ranging from 0.1 to 3,000 ha in Maryland, Pennsylvania, West Virginia, and Virginia, the percentages of forest cover within 2 km and the forest patch area were significant habitat variables for 40 and 38 species, respectively, of 75 species studied; 26 birds were considered area sensitive.[56]

It may take 75–100 years, or more, for cleared forests to regenerate and mature. Forest floor species such as salamanders[65] and herbaceous plants[66] have limited dispersal ability and may take as many additional years to recolonize regrown forests.[67] The guild of forest herbs, often diverse and abundant in mature Appalachian forests, contains many species vulnerable to environmental changes.[66] Logging or clearing reduces herb diversity, and the herb stratum may take several decades to recover. Herbivory by white-tailed deer (*Odocoileus virginianus*) is harmful to many forest herbs; it is possible that clearing for wellpads, roads, and pipelines may create a landscape that will support more deer and may subject forest herb populations to more intense grazing. One study reported that forests that are less than 70 years old supported fewer rare lichens and bryophytes than older forests;[51] this observation may pertain to young forests that develop following abandonment of HVHHF installations.

Roads and pipelines

Roads act as corridors for the spread of nonnative weeds.[35,68,69] Nonnative or weedy native plants will colonize disturbed soils at roads,[35,70] wellpads, compressor stations, and pipelines, and spread from there into forests and other habitats. This has occurred at energy development sites in western North America.[71] Among possible nonnative weeds that could colonize eastern HVHHF sites are common reed (nonnative haplotype of *Phragmites australis*), stiltgrass (*Microstegium vimineum*), Japanese knotweed (*Polygonum cuspidatum*), spotted knapweed (*Centaurea stoebe*), mugwort (*Artemisia vulgaris*), angelica tree (*Aralia elata*), autumn-olive (*Elaeagnus umbellata*), tree-of-heaven (*Ailanthus altissima*), and empress tree (*Paulownia tomentosa*). These plants thrive on habitats resulting from cut-and-fill, and are colonizing recent disturbances from surface mining, roads, and gas pipelines in the Catskill Mountains and Hudson Highlands of New York and other eastern regions.[72] Common reed disperses along roads, and from there, into adjoining undisturbed habitats,[73,74] where it may adversely affect plant and animal assemblages. The combination of disturbed roadside habitat and salinization from deicing salts is favorable for common reed. Vegetation of pipeline rights-of-way is managed by mowing or spraying herbicide; runoff or spray drift may affect rare native plants in adjoining habitats.

Many forest songbirds avoid roads, trails, pipelines, and human activities.[75] In western Canada, territories of the ovenbird (*Seiurus aurocapillus*) straddled 3-m-wide cleared seismic exploration lines, but did not straddle 8-m-wide lines, leading to local population declines.[75] In another example, red-backed salamander (*Plethodon cinereus*) was less abundant near gravel roads in mature forests in Virginia; this influence of roads on red-backed salamander appeared to be due to dessication of soils.[76] Some access roads and pipelines cross wetlands and streams, potentially creating barriers to movement of water and organisms. It takes an estimated 6,800 truck trips to fracture a single well.[77] Many amphibians, reptiles, birds, and mammals are vulnerable to road mortality; in Ontario, numbers of dead frogs increased, and nearby breeding choruses decreased in intensity, in proportion to the amount of traffic on roads.[78]

Hydrological alteration

Many organisms of streams, wetlands, and temporary ponds require certain patterns of water levels and flows through the year (the hydropattern).[79] Hydrological changes, including the withdrawal of surface waters, and increases in runoff caused by deforestation and impervious surfaces of wellpads and access roads, presumably affect the hydropatterns of streams,[80] floodplains, wetlands, intermittent pools (vernal pools), springs, seeps, shallow groundwater, and karst complexes. Withdrawals from lakes and rivers for fracturing wells might reduce minimum instream flows in the summer. Stream fishes, including brook trout (*Salvelinus fontinalis*), and aquatic invertebrates that must remain in water during summer, such as crayfishes and stoneflies, may be adversely affected by reduced summer flows.[81] Reduced flows may also decrease dissolved oxygen, increase deposition of fine sediment, and increase water temperatures, causing macroinvertebrate species richness to decrease and community composition to shift toward forms tolerant of these conditions.[82] Other species that could potentially be affected include freshwater mussels (Unionoidea), diverse in the Marcellus–Utica region, that are sensitive to hydrology, water quality, and siltation of rivers.[83,84] Hellbender (*Cryptobranchus alleganiensis*), a giant aquatic salamander, requires cool, well-oxygenated, swift streams and is also sensitive to siltation and pollution.[85–87]

In addition, withdrawal and disposal of water could potentially affect groundwater tables and flows, changing groundwater inputs to streams or wetlands. Impacts may be greater during droughts, or where there are competing uses of water, such as in agriculture.[3,13] At a threshold of 10–20% cover by impervious surfaces in a watershed, water quality and species diversity decrease in streams;[80,88–90] in some HVHHF landscapes, wellpads and access roads cover more than 10%.[1] Because of the density of HVHHF infrastructure on the landscape, and other impacts from siltation and chemical pollution, there may be cumulative impacts to wetlands and streams. Reduction of forest cover in watersheds may also have long-lasting effects on stream biodiversity.[91]

Noise

At HVHHF installations, diesel compressors run 24 h/day, and the noise can be heard from long distances.[20] Continuous loud noise from, for example, transportation networks, motorized recreation, and urban development can interfere with acoustic communication of frogs, birds, and mammals, and cause hearing loss, elevated stress hormone levels, and hypertension in various animals.[92] One study showed that gas compressor station noise in Alberta reduced ovenbird pairing success.[93] In pinyon-juniper woodland of New Mexico, breeding bird species richness was greater, species composition different, and overall nest density similar near gas wellpads without compressors compared to wellpads with compressors, but daily nest survival was higher near pads with compressors due to less predation by western scrub jays (*Aphelocoma californica*).[94] In a comparison of breeding birds near wellpads with and without compressors in the boreal forest, total density and densities of one-third of the individual species were lower at the compressor sites.[95] Bats avoid continuous loud noise and it may impair foraging efficiency.[96–100]

Light

Installations are brightly lit at night,[20] especially wellpads during drilling and fracturing and compressor stations continuously. Artificial night lighting variably affects different taxa; for example, adult moths and aquatic insects may be attracted and killed, whereas various species of bats may be harmed or benefited.[96,101,102] Night lighting potentially disrupts populations of stream insects, in turn affecting food webs and ecosystem function.[103] Mortality, reproduction, and foraging of many other animals are affected negatively or positively.[101] Polarized light pollution from artificial surfaces, especially smoother, darker surfaces including pavement, vehicles, and waste oil, creates another visual disturbance.[104] Animals that orient to polarized light, including many invertebrate and vertebrate taxa, may be killed or have their reproduction disrupted. This potential impact of HVHHF installations has not been studied.

Air quality

Air emissions, including diesel exhaust from compressors and trucks, volatile organics from fracturing fluids, ground-level ozone resulting from their interaction, and road dust, affect air quality around HVHHF sites.[105] Diesel smoke contains mutagenic and carcinogenic polycyclic aromatic hydrocarbons (PAHs)[106] that could affect animal health. In a relevant study, nitrogen oxides from vehicles affected mosses within 50–100 m of roads in England;[107] trees were adversely affected within the same distances, but the haircap moss *Polytrichum commune* showed a decline in frequency with distance from heavily traveled roads.[108] It is possible that diesel exhaust at HVHHF sites could produce similar effects. Lichens are especially sensitive to sulfur dioxide and other air pollutants,[36,39,109,110] and are harmed by road dust, as are sphagnum mosses.[111]

Range-restricted species

A species that has a large part of its geographic range in the Marcellus–Utica region may potentially be at risk of extinction from HVHHF impacts (especially in combination with other widespread environmental change). A recent study[8] analyzed 15 plants, butterflies, fish, amphibians, and mammals with geographic ranges overlapping the Marcellus–Utica region by 36–100% (Figs. 2 and 3). Although most of these species are considered sensitive to forest fragmentation, habitat alteration, or water quality degradation, lungless salamanders (Plethodontidae; eight species analyzed) seemed especially at risk. Many species of invertebrates, higher plants, and cryptogams whose ranges have not been mapped in detail may be quasi-endemic to the region.

Species with larger geographic ranges may nonetheless have important population components or seasonal habitats within the Marcellus–Utica region. The Virginia big-eared bat (*Corynorhinus townsendii virginianus*) occupies 15 limestone caves, 11 of which are in West Virginia.[112] Limestones are often highly porous to water pollution; therefore, cave species could potentially be at greater risk of being affected by HVHHF.

In each state, because of historic, political, social, and economic differences, and genetic differences within many species, environmental impacts on, and management of, rare species differ. Therefore, a species that is restricted to the Marcellus–Utica region within one state could potentially be at higher risk. In Pennsylvania, all known populations of the green salamander (*Aneides aeneus*), and 73% of populations of the snow trillium (*Trillium nivale*), are in localities with a high probability of HVHHF.[1] In New York, bluebreast darter (*Etheostoma camurum*), spotted darter (*E. maculatum*), banded darter (*E. zonale*), and variegate darter (*E. variatum*) are apparently confined to the Marcellus region;[113] these stream fishes are likely to be sensitive to salt and sediment pollution.[114,115]

Species potentially benefiting from HVHHF

Many native organisms use habitats created by construction or abandonment of industrial facilities, such as forest edges or bare soil. Some native bees and wasps dig nest burrows in bare soil, and reptiles often lay eggs in disturbed soils of road and railroad verges. Snakes, including timber rattlesnake (*Crotalus horridus*), are attracted by warm pavement in cooling weather. Several birds nest on bare or sparsely vegetated soil, including mallard (*Anas platyrhynchos*), common nighthawk (*Chordeiles minor*), killdeer (*Charadrius vociferus*), and spotted sandpiper (*Actitis macularia*), and many birds dust bathe on bare soils. White-tailed deer have been shown to be attracted to soils where HVHHF wastewater had been land-applied;[15] porcupine (*Erethizon dorsatum*)[116] and many butterflies[117] would also be attracted to salt. Metal-tolerant vascular plants and mosses could grow in these situations.[118] Postindustrial sites in England are important habitats for beetles, including rare species.[119]

Species of southern affinities would be attracted to wellpads and their peripheries due to solar warming. For example, water-filled wheel ruts and rain pools would serve as larval mosquito habitats; in Wyoming, there was a 75% increase in 5 years in potential mosquito larval habitats in ponds holding wastewater from coal bed gas drilling.[120] Access roads with numerous, long-lasting rain pools might support the globally rare feminine clam shrimp (*Cyzicus gynecia*).[121] It is possible that some grassland and shrubland species might colonize decommissioned facilities if they are extensive or adjoin other nonforested habitats. Most organisms able to colonize active or abandoned installations may be

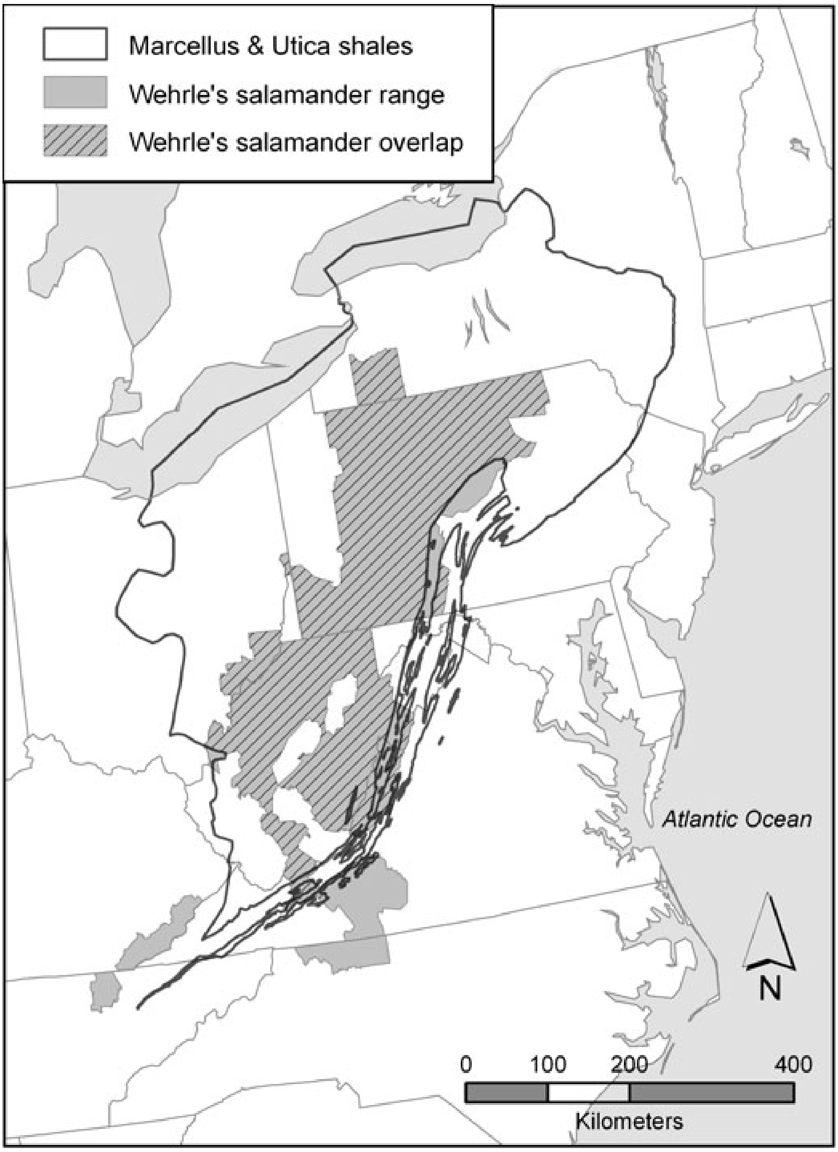

Figure 2. Distribution of Wehrle's salamander (*Plethodon wehrlei*) in relation to the Marcellus–Utica shale region. Reprinted with the permission of Cambridge University Press.[8]

common species and ecological generalists. Rare or sensitive species that are small or require only small habitat patches (e.g., land snails, millipedes, certain insects) may persist in forest patches between wellpads, and some organisms might escape predators or competitors in fragments.

Cumulative impacts

In the Marcellus–Utica region, HVHHF constitutes landscape- and regional-scale activities and impacts. Many thousands of wellpads will be distributed across the 280,000 km^2 region. Each wellpad will likely be drilled several times, and successful wells will be fractured multiple times during their 40- to 50-year life span.

Widespread environmental changes other than those produced by HVHHF also affect eastern biodiversity,[6,122] including coal mining, logging, agriculture, urban sprawl, accelerated climate change, acidification, eutrophication, chemical

Figure 3. Distribution of tongue-tied minnow (*Exoglossum laurae*) in relation to the Marcellus–Utica shale region. Reprinted with the permission of Cambridge University Press.[8]

contamination, altered fire regimes, emerging pathogens and parasites, and nonnative species spread. For example, most tree species are not shifting latitudinal ranges to keep pace with climate warming, and the ranges of many species are shrinking.[123] Such large-scale changes could potentially interact synergistically with the HVHHF impacts on forest biota as they accumulate across space and time. One study suggested that the effects of HVHHF on stream water quality will accumulate across watersheds.[3] In a meta-analysis of the effects of roads, power lines, and wind turbines on birds and mammals, bird populations were reduced as far as 1 km, and mammal populations were reduced as far as 5 km, from roads and infrastructure.[124] If this finding applies to the wellpads, gas compressors, and roads associated with HVHHF, the corresponding buffers around each installation needed to protect birds and mammals (3.1 km^2 and 78.5 km^2) are larger than the current spacing units for well density in Pennsylvania (1–2.5 km^2) and those projected for New York (2.6 km^2).[16]

Discussion and conclusions

Biodiversity impacts of HVHHF are similar to the impacts of many industries, although the chemical complexity and geographic extent are unusual. The major, long-term effects on biota likely to propagate through landscapes are habitat loss and fragmentation, chemical pollution, degradation of water quality, and hydrological alteration; other impacts, including noise, light, and air quality, may be more local and short-term. Biota vulnerable to HVHHF impacts include many native organisms that are important either for subsistence or in broader markets, such as medicinal plants (e.g., goldenseal (*Hydrastis canadensis*)),[125] edible fungi, brook trout and other sport fishes,[1] game birds and mammals (e.g., wood duck (*Aix sponsa*)), furbearers (American mink (*Mustela vison*), river otter (*Lontra canadensis*), common muskrat (*Ondatra zibethicus*)), and "watchable" wildlife (e.g., many forest-breeding birds). For example, studies suggest that HVHHF may affect trout habitats via water temperature increase, siltation, and heavy metals.[126,127]

Many of the biodiversity impacts of HVHHF might be reduced by zero-loss management of chemicals, wastewater, soil, and other pollutants, but this is a challenge considering the record of leaks, spills, fugitive emissions, and disposal. Water use and truck traffic can be reduced by reusing more wastewater, but similar amounts of pollutants will require disposal. If it eventually becomes possible to drill horizontally several kilometers, fewer wellpads would be needed, thus reducing fragmentation, and allowing more wells to be sited next to highways or on derelict lands, such as abandoned strip mines. However, pipelines would still fragment forests and impinge on sensitive habitats.

Forest loss and fragmentation are considered among the most serious threats to biodiversity.[128,129] Many forest species, particularly birds, require extensive tracts of continuous forest to maintain viable breeding populations. Inasmuch as the eastern United States was extensively deforested during the 1800s, one might ask whether current deforestation and fragmentation matter to biodiversity. At a maximum, only half of the east was deforested at once because clearing was not concurrent across the region; asynchronous deforestation probably prevented extinction of many species.[129] Yet deforestation contributed greatly to the extinction of the passenger pigeon (*Ectopistes migratorius*)[130] and the temporary loss or rarity of red-shouldered hawk (*Buteo lineatus*), wild turkey (*Meleagris gallopavo*), pileated woodpecker (*Dryocopus pileatus*), American beaver, black bear (*Ursus americanus*), fisher (*Martes pennanti*), and white-tailed deer from most of New York State and probably large regions elsewhere in the eastern United States.[131] Most of these species have recovered with the redevelopment of extensive forests, even to the point of overabundance of deer, bear, and turkey. Forest cover in the east is decreasing again,[132] and forests of the conterminous United States are fragmented to the degree that edge effects occur throughout most forested landscapes.[133] Fragmentation also affects grasslands and their breeding birds.[16,134] The many other stressors affecting freshwater organisms[135] may be compounded by water pollution and hydrological alteration from HVHHF.

Biotas are impoverished in industrial and urban areas, although many species thrive, including some rare species.[136–138] Few empirical data are available on biodiversity impacts of eastern HVHHF, although activities are already widespread and potentially will occur throughout 280,000 km^2. HVHHF is also intensive, causing great changes to habitats at HVHHF installations and to the intervening landscapes. Consideration of a broad spectrum of taxa and guilds suggests potential HVHHF risks to biodiversity, particularly organisms that are specialized in their habitat, require unpolluted freshwater with natural hydropatterns, or have small geographic ranges concentrated in the Appalachian Basin. Impoverishment of species assemblages likely will lead to diminution of ecosystem functions and services.[139]

It is expected that an HVHHF installation will be decommissioned and the site restored after 40–50 years; procedures may include regrading, removing roads and impoundments, restoring topsoil, and native planting.[21] Restoration will accomplish more if it is targeted at habitats and species of conservation concern, rather than simply restoring forest or grassland. For example, CWD is important for salamanders, snakes, invertebrates, bryophytes, and lichens. Coarse woody debris could be stockpiled when a site is cleared and used for restoration of a nearby site that is being decommissioned. Construction, operation, and decommissioning of HVHHF facilities, if viewed as a mosaic across the landscape, could be better managed to reduce impacts on biodiversity. Most research on wild organisms is restricted in space and time; thus, we are not well equipped to understand and conserve on large scales.[140] Most regulation of HVHHF has occurred at the level of the individual wellpad; however, to protect biodiversity and ecosystem services, it may be necessary to plan and regulate at the level of the whole Marcellus–Utica region.

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Conflicts of interest

The author declares no competing financial interest.

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