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A Consideration of Wildlife in the Benefit-Costs of Hydraulic Fracturing: Expanding to an E3 Analysis

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Abstract: High-volume hydraulic fracturing (“fracking”) for natural gas in the Marcellus Shale (underlying about 24 mil ha in New York, Pennsylvania, Maryland, West Virginia, Ohio, and Virginia) has become a politically charged issue, primarily because of concerns about drinking water safety and human health. This paper examines fracking in the Marcellus region, and the tradeoffs between the energy and economic potential of natural gas extraction and the environmental impacts on wildlife. Therefore, we introduce a new E3 analysis that combines the costs and benefits as regards energy, economics, and the environment. The Marcellus Shale has the most proven reserves of natural gas of any basin in the United States, at 129 trillion cubic feet. Income from natural gas development comes primarily from direct and indirect jobs, and induced jobs (those created when direct workers spend their earnings in a community), taxes and fees, and royalty and lease payments to rights holders. Fracking, however, has detrimental effects on wildlife and wildlife habitats. Terrestrial habitat effects are primarily due to landscape fragmentation from the clearing of land for pipeline and well pad development, which often removes mature forest and creates open corridors and edge habitats. An increase in forest edge and open corridors is associated with shifts in the bird community, as generalist species that do well around people increase in abundance, while forest specialists decline. Invasive plants associated with disturbance further degrade forest habitats. Aquatic habitats are also affected, both directly and indirectly. Hydraulic fracturing requires up to 20 mil L of water per well fracture, most of which comes from surface water sources in the Marcellus region. The removal of water, especially in smaller headwaters, can increase sedimentation, alter water temperature and change its chemistry, resulting in reductions in aquatic biodiversity. Given the reality that hydraulic fracturing will continue, there is a need to develop practices that best minimize negative impacts on terrestrial and aquatic habitats, as well as policies and the resolve to enforce these practices. To achieve a more sustainable balance between economic, energy, and environmental costs and benefits, we recommend that industry, scientists, non-governmental organizations, mineral rights holders, landowners, and regulators work together to develop a set of best management practices that represent the best knowledge available.

Keywords: best management practices; economics; energy; environment; habitat; hydraulic fracturing; Marcellus; policy; shale; wildlife



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1. Introduction

Shale is formed over geologic time, when layers of sediment compact under heat and pressure into rock with low horizontal permeability and even lower vertical permeability [1,2]. Gas is formed in the shale when organic material trapped between the layers decomposes anaerobically [3]. Shale gas is typically nearly 90% methane, along with small

percentages of other volatile organic compounds such as butane, propane, and ethane [4,5]. Shale gas basins occur across much of the United States, with the largest shale formation in North America being the Bakken formation in North Dakota and Montana in the United States, and Saskatchewan and Manitoba in Canada. The third largest U.S. formation is the Marcellus shale basin, covering an area of about 24 mil ha in New York, Pennsylvania, Maryland, West Virginia, Ohio, and Virginia [4] (Figure 1). The deeper Utica shale basin—currently trailing the Marcellus in activity and production—underlies much of the Marcellus and extends further into Ohio and New York [6].

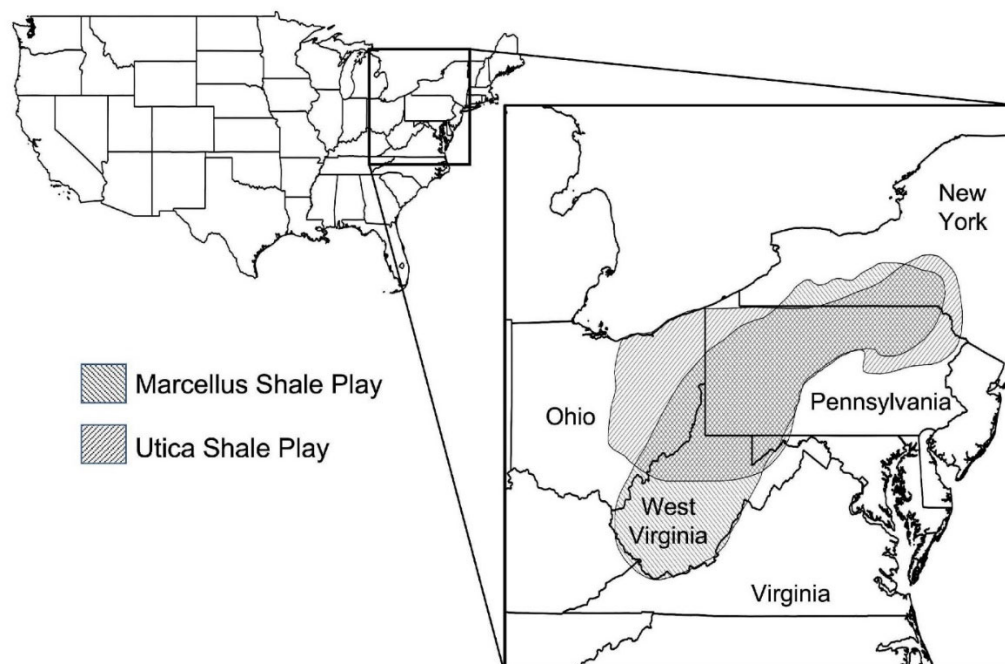


Figure 1. Marcellus and Utica shale plays in the United States.

To determine the best places to drill, gas companies usually perform seismic testing using explosives or vibroseis trucks (confined to roads) to create seismic waves [7]. After selecting potential drill sites in the Marcellus Basin, an average of 1–2.7 ha is usually cleared for construction of the wellhead and supporting structures, such as fluid storage tanks or evaporation pits [4]. Producers must also build roads to the well pad and upgrade existing roads to handle the heavy truck traffic. Pipelines, along with the other associated infrastructure for a well (roads, impoundments, etc.), require an average of 2.3 ha of cleared land per well [8]. All natural gas pipelines, however, including the large interstate transmission (aka “main”) lines, currently total about five million km of pipeline that link natural gas production areas and storage facilities with consumers in the U.S. [9], with much more pipeline construction anticipated, increasing transmission capacity [10]. Additional land may also be cleared to build housing for workers, as in Athens, Pennsylvania, where a facility to house and train 280 workers was built by the Chesapeake Energy Corporation on 5.3 ha of previously undeveloped land [11].

Two newer technologies have been combined to more efficiently and economically mine shale gas plays: horizontal drilling [1,4] and hydraulic fracturing, also known as “fracking” [4]. Fracking is a multi-step process, proceeding initially with the injection of 15% hydrochloric (muriatic) acid solution to remove drilling mud and cement from the interior of the upper portion of the well [4], followed by the injection of water mixed with polyacrylamide or mineral oil to reduce friction, and finally fracturing liquids (most commonly a proprietary mixture of many chemicals, such as surfactants, pH adjusting agents, gelling agents, corrosion inhibitors, paraffinic solvents, biocides, breakers to facilitate extraction, and round quartz sand [4] to force the fluid into the shale and hold

the fractures open [12,13]). When the high-pressure pumping stops, the fluid and natural gas begin to flow back to the surface. Approximately 20–25% of the injected fluids will flow back through the wellhead, while the rest of the fluid remains trapped in the shale formation [4]. The flowback water is collected and either stored for re-use or treated as wastewater. Drilling and fracking a single well takes several weeks to complete, and requires between 10 and 20 mil L of water [4].

Hydraulic fracturing for natural gas is politically a highly-charged, fractious topic. Proponents point to the potential of the technique to produce enough natural gas within the United States to reduce the country's dependence on imported natural gas. Opponents are concerned about the increasingly known and potential future environmental effects of fracking, including human-induced climate change [14–16]. While valid arguments can be made on both sides of the issue, the debate is anthropocentric. Only humans use natural gas and, for the most part, those protesting fracking's environmental impacts are primarily concerned about human health, including drinking water quality, along with air, noise and light pollution, and toxic radioactive releases [17].

2. Methods

This paper examines fracking from a wildlife perspective, with particular emphasis on the impacts to wildlife habitats in the Marcellus Shale region in the northeastern United States. In order to fully understand natural gas development policy and impacts, we review it from three different dimensions, collectively called an “E3 analysis”, including:

1. Energy potential—i.e., how much gas is there and how does it impact the overall natural gas resource in the United States?
2. Economics—i.e., what are the costs and the benefits for the industry producers, the public, and other stakeholders?
3. Environmental impacts—i.e., what are the environmental effects on wildlife and wildlife habitat?

In reviewing these dimensions, it is important to consider both short- and long-term impacts. Collecting and analyzing data from all three of these dimensions allows us to understand the points of view of multiple stakeholders involved, including industry, mineral rights owners, landowners, regulators, and the public who bear the cost of the loss and degradation of wildlife and the wildlife habitat (Figure 2). Further, it provides a comprehensive set of variables to be used in any decision-making process to determine best management practices for future natural gas extraction, while reducing environmental impacts.

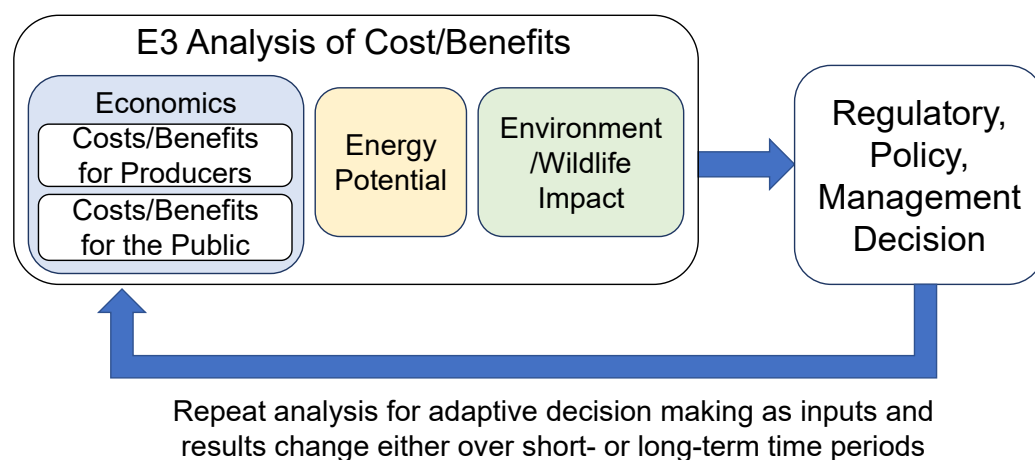


Figure 2. Balancing components of E3 analysis.

3. E3 Analysis: Energy Potential

The United States produced 33.9 tcf (trillion cubic feet) of natural gas in 2020, of which 26.3 tcf (about 79%) was shale gas [18]. The United States Energy Information Administration (USEIA) [19] projects that the United States will produce 42.9 tcf annually by 2050, with 39.7 tcf (>90%) from shale plays. Much of the increased production will come from the Marcellus and Utica shale basins. Given current annual natural gas consumption in the United States (30.5 tcf), the current total proved U.S. reserves of shale gas (318 tcf) could last approximately 10.4 years; this supports the concomitant consideration of shale gas as a “bridging” energy source, as well as the need to develop more sustainable energy sources, such as solar, wind, wave, hydro, tidal, etc., as soon as possible.

4. E3 Analysis: Economics

Several factors drive the development of shale gas plays, including energy independence from other nations, potential reductions in greenhouse gas emissions, and economics. Natural gas is “big business” in the United States, and its financial impact goes far beyond what consumers pay to heat their homes. From the moment a well location is identified, money is involved. Natural gas operators employ people to investigate potential wells, pay landowners to lease their property, and provide some financial assurance (such as bonds) that there will be money to plug a well if the operator fails to do so. Jobs are created (at least temporarily) to build an infrastructure of roads, pipelines and drill wells. Sales of the associated equipment and its servicing are made to those creating the infrastructure. Employees, in turn, spend money in the local community and support its economic infrastructure.

Along with the income that natural gas development brings, though, there are also expenses to communities. Additional civil services may be required, including zoning officials, emergency responders, and road and bridge maintenance costs. Additional burdens are often incurred to clean-up and plug orphaned wells [20]. There are also employment costs; the USEIA [19] estimates potential losses of jobs in other energy sectors, as jobs in natural gas increase. There are also the less tangible costs to consider, such as losses of habitat, or reductions in the quality of habitat for wildlife species. Changes in biodiversity can impact outdoor recreation and its economic effects on a region, as well as the loss of valuable ecological services provided by the wildlife species that decline in numbers [21–23].

4.1. National Pricing and Pricing Trends

The non-renewable energy sector comprises approximately 5.6% of the United States Gross Domestic Product (GDP), contributing approximately USD 1.2 trillion annually to the U.S. economy [24,25]. Natural gas alone contributes about 12% of that (USD 150 billion in 2012) [25].

Like most commodities, there are different listed prices at different points in the production cycle. For natural gas, spot prices (the current market prices) are usually determined by the price at the Henry Hub, a natural gas pipeline hub in Louisiana. Spot prices are generally much lower than consumer prices, which vary regionally and by sector. As of December 2021, the Henry Hub price was USD 3.57/MMBTU (one million British Thermal Units; equivalent to ~1000 ft³), with a 12-month average price of USD 3.89/MMBTU [26]. By comparison, the ten-year high Henry Hub price for natural gas was USD 14.49/MMBTU in December 2005 and the low was USD 1.34/MMBTU in December 1998 [26]. The USEIA, in its 2021 Annual Energy Outlook, predicts that natural gas prices will remain relatively low throughout 2050, due to the increased production of natural gas from shale formations [19].

4.2. Income from Natural Gas

The primary economic benefit that the natural gas industry claims when bringing operations into a region, such as the Marcellus Basin, is the creation of jobs. The jobs affected by industry fall into three categories: direct, indirect, and induced [27,28]. Direct jobs are those that fill the operator’s immediate labor needs, such as road construction

workers, drilling equipment operators, attorneys to handle the legal services required to obtain leases, and other direct needs. Indirect workers support the industry and include equipment and material suppliers. Induced jobs are those that are created when the income from the other categories is spent in the community in which it is earned, to purchase local goods and services. These include restaurant workers, local merchants, hotel operators, etc.

Within the Marcellus region, estimates of the number of jobs created by natural gas operations vary widely. Early estimates of jobs created in Pennsylvania ranged from 20,000 to over 100,000, including direct, indirect, and induced jobs [29,30]. Some of these jobs were temporary jobs filled by out-of-state workers, while many were more long-term jobs filled by state residents. As of 2019, natural gas production accounted for approximately 14,000 direct jobs in Pennsylvania, as natural gas production in the state has decreased [31].

Another major source of income from gas operations is royalties and lease fees paid by operators to mineral rights holders and landowners. In the Marcellus region, mineral rights and surface rights are separate and may be held by different entities, and in most cases, mineral rights prevail. Royalties are paid as a percentage of the value of the produced gas, which invariably declines over time, as the immediate resource and output declines [32]. Some states have minimum percentages that must be paid to the rights holder (e.g., Pennsylvania requires a minimum of 12.5% in royalty payments [33]); however, the industry has increasingly attempted to add “post-production costs” reducing such royalties, with the Marcellus Shale Coalition (industry-subsidized) even providing a toolkit on how to best justify such costs [34]. Land leases grant the operator access to the surface landscape, such as the well pad or pipeline. They are usually flat fees paid regardless of production from the well. None of the states in the Marcellus directly report income from either royalties or leases, but estimates from tax records range from USD 963 million from 2010 to 2016 in West Virginia, to USD 7.1 billion for those same years in Pennsylvania [33,35]. Landowners can also sell the timber that is produced when the land is cleared. For example, Pennsylvania leases of state forest land for gas development from 2008 to 2016 realized USD 17 million in timber sales from the clearing of that land [36].

Other sources of revenue from natural gas operations in a region are from taxes and fees. In the Marcellus region, state and local governments receive increased taxes through income taxes on workers and corporations, royalty taxes paid to leaseholders, and severance tax or impact fees paid directly to governments by the operators. A severance tax is a tax imposed by a state on an operator who removes a natural resource from land within that state. Impact fees are fees paid to state or local governments to reimburse them for the impact an operation has had on their jurisdiction (e.g., to compensate a county for damage to its roads or for the increased costs of permit processing). In the Marcellus region, Pennsylvania and New York are the only states without severance taxes on any natural resources, including natural gas. New York currently has no taxes or impact fees specific to natural gas production, as hydraulic fracturing is currently banned in the state. Pennsylvania has only impact fees. West Virginia imposes a 3% severance tax on the gross value of the natural gas produced. Ohio currently has a severance tax of approximately USD 0.025/mcf (thousand cubic foot) of natural gas produced, regardless of sales.

Other tax revenues can increase with the influx of natural gas production in a region as well. Costanzo and Kelsey [37] found that Pennsylvania counties with ≥ 150 wells reported an increase in state sales tax revenue of 11.36% from 2007 to 2010. They also found that personal income tax revenues increased more in counties that had more wells than in those with fewer wells or none at all (6.96% for counties with ≥ 10 wells vs. 3.08% for counties with between 1 and 9 wells vs. 0.89% for counties with no wells).

4.3. Costs of Natural Gas Production

As with economic benefits, there are direct and indirect costs of natural gas production. Direct costs include all the costs incurred by the operators (e.g., leasing fees, drilling costs, operating costs, reclamation costs, bonds) and those incurred by local governments, such as officials to process permits. Indirect costs include the increased long-term road maintenance

costs required by heavy truck use, increased emergency services costs due to increased worker populations and higher risk occupations, and even potential decreases in property values. One survey in Washington County, Pennsylvania, showed that home sale prices decreased in correlation with the proximity of the home to a natural gas well, especially if the home's water supply came from a private well [38].

The USEIA estimates that the operator's total average cost per well for drilling and completion in the Marcellus Basin in 2015 was approximately USD 6 million [39]. Even at the end of a well's production lifespan, there is a cost. Raimi et al. [40] found that costs to plug a well and reclaim the well pad in Pennsylvania ranged from <USD 4000 to >USD 469,000 with a median cost of USD 24,000, depending on the type of landscape to be restored. However, when wells are orphaned (inactive and unplugged wells with unknown or insolvent operators), such costs fall to the public, revealing how insufficient bonds put up by operators are [20,41].

Agricultural landscapes are less expensive to restore than those that were once mature forests. Completely removing paved or gravel surfaces, regrading, adding topsoil, and planting appropriate native plants are more expensive than simply filling an impoundment pit and spreading non-native grass seed. Since most regulations do not specify exactly how the well pads are to be restored, operations may be inclined toward the cheaper alternatives, unless individual lease agreements stipulate otherwise.

Overall, natural gas permit applications in Pennsylvania, Ohio, and West Virginia—the three states that currently allow the technology—are in decline, and were even before the COVID-19 pandemic (Figure 3). By far, most permits issued have been for new horizontal wells extending off existing vertical wells, using existing well pads, pipelines, and other infrastructure. This significantly reduces the cost to operators for new wells and decreases the impact on the landscape.

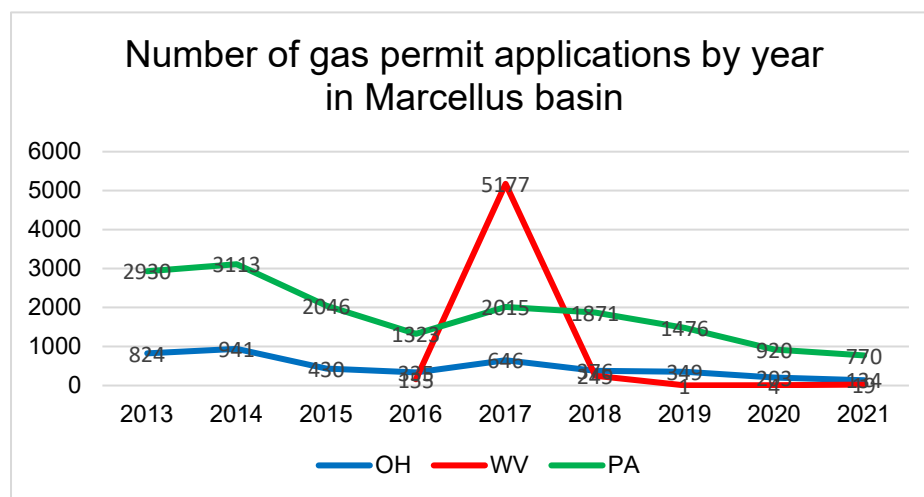


Figure 3. Number of natural gas permits issued per state by year (2013–2021) in the Marcellus Basin, USA. (Source: Ohio Department of Natural Resources, West Virginia Department of Environmental Protection, Pennsylvania Department of Environmental Protection).

In addition to the easily quantifiable costs of natural gas development, there are also less tangible costs. Changing the use of the land from either agricultural or forest incurs a loss of ecological services. Ecosystems, such as those in forests, provide services that can be valued. These ecosystem services are classified into four categories: provisioning services (timber, water, raw materials, etc.), regulating services (erosion prevention, water quality control, carbon sequestration, etc.), supporting services (biodiversity), and cultural services (aesthetic, recreational, etc.) [42]. DeGroot et al. [43] analyzed over 300 publications with global ecosystem service estimates, and summarized them by the type of ecosystem (e.g., forest, wetland) in International USD/ha. The 2007 average estimate for temperate forest

land was USD 3013/ha $\pm$ USD 5437/ha, with a range of USD 278–16,406/ha and a median of USD 1127/ha (2022 equivalent = USD 1647/ha). Given the amount of land cleared for a well pad (1–3.6 ha), the ecosystem service loss was quantified in 2007 at an average of USD 3013–10,847 per well pad (2022 equivalent = USD 4405–15,858).

Calculating the cost of loss of land use that was previously agricultural varies from state to state. Pennsylvania and Ohio place specific values on each ha of land of agricultural use for tax purposes, while West Virginia and New York do not (those states provide discounted tax rates for farm use). In Pennsylvania, the agricultural use of land was valued at USD 272–USD 671/ha (USD 671–1658/acre) in 2021, depending on the specific category of the land [44]. In Ohio, cropland averaged USD 307/ha (USD 759/acre) [45].

Overall, natural gas production yields a net profit. The income produced from the sales of natural gas, jobs created, taxes and fees paid to government agencies, and royalties and lease fees paid to mineral rights holders and landowners exceeds the production and reclamation costs, the loss of ecological services, and the costs of municipal services; however, whether those profits are equitably distributed remains an issue. For example, costs such as the loss of ecological services from the change of land use from forest to well pad are incurred by all local residents, but the income derived from that change is very likely not realized by all.

5. E3 Analysis: Environment

Most counties in the Marcellus Shale region are forested over more than 50% of the land area, while the remainder is primarily agricultural, commercial and residential development, with some areas of wetland [46]. The Marcellus and Utica shale region encompasses five physiographic areas, demarcated by distinct geology and topography: the Lower Great Lakes Plain, the Allegheny Plateau, the Ohio Hills, the Mid-Atlantic Ridge and Valley, and the Northern Cumberland Plateau. The Marcellus–Utica region provides habitat for hundreds of species of mammals, birds, fish, reptiles, amphibians, and mollusks, and the primary effect of shale gas extraction on these species is most likely to be on their habitats [47]. This section examines the potential impacts on terrestrial and aquatic habitats.

5.1. Terrestrial Habitat Effects

The construction of natural gas wells in forested areas requires the complete clearing of the land for the well pad, and supporting infrastructure, pipelines and roads, needed to access the site. The well site is kept cleared during the production life of the well; however, it is generally replanted at the completion of operations at the site, depending on state requirements [4]. Effects on wildlife caused by the development of a natural gas facility are both direct and indirect. Clearing land and building the well pad, associated roads, and pipelines have the potential to indirectly affect wildlife by lowering the habitat quality and reducing habitat availability for resident and migratory species. The clearing of forested land tends to be permanent, especially along pipelines, with continued maintenance to prevent regrowth [48]. Direct effects include the displacement of residents, losses from vehicle collisions on new roads transecting previously intact habitat, and the disruption of nearby nests or dens.

The clearing of forested land causes habitat loss and fragmentation, and an increase in habitat edges within the landscape, where one type of habitat abuts a different type (e.g., intact forest adjacent to a clearing). The introduction of edges in a previously undisturbed habitat can change the variety and abundance of the species that use it, increasing those species that are habitat generalists and able to do well around people, and decreasing those species that require core forest habitat [49–51]. The effects of edge habitats on bird species shows that birds, especially passerines, are particularly affected by the introduction of fragmentation and edges into the landscape [51–57], while natural gas sites in grasslands are associated with an increase in non-native invasive plants, a reduction in native ground cover, and changes in soil properties [58], which could reduce nesting attempts or success. Typically, concern is due to increased brood parasitism by brown-headed cowbirds

(*Molothrus ater*) [49,55,59–61] and increased nest predation by species such as corvids, raptors, raccoons (*Procyon lotor*), and snakes [52,55,60,62–64]. Shale gas development within Pennsylvania and West Virginia's contiguous forests showed a decrease in forest-interior songbirds and an increase in synanthropic or human-associated species [21,56].

Bats are also affected by landscape fragmentation and edges [65], and clearing land for natural gas extraction could impact federally endangered species, such as the Indiana Bat (*Myotis sodalis*), the federally threatened Northern long-eared bat (*Myotis septentrionalis*; recently proposed by the USFWS to be elevated to Endangered status; 23 March 2022), and the little brown bat (*Myotis lucifugus*; currently considered an “at risk” species) that prefer foraging in interior forest structures.

In addition to creating edges in a landscape, roads also present other hazards to wildlife, although the impact is reduced when they are built through already disturbed landscapes, such as agricultural fields [66]. For some small mammals and herpetofauna, roads can be a barrier to movement [67–69] and have the potential to create isolated subpopulations. Traffic on roads associated with gas well sites is also a direct source of mortality through vehicle collisions, especially during breeding and wintering seasons [70]. Additionally, roads can become corridors, facilitating the spread of invasive plant and animal species, which can cause losses of native habitat [71].

In addition to landscape disturbances from the construction and operation of the wells, natural gas production can cause noise disturbances. The compressor stations along gas pipelines typically produce between 75 and 90 dB(A) continuously, and can reach 105 dB(A) [72]. Bayne et al. [72] found that increased noise levels could be detected at distances of over 1 km into forested areas. Birds are particularly susceptible to increased noise levels associated with natural gas pipelines, which have been shown to affect passerine density up to 700 m into the interior of the forest [72]. Bayne et al. [72] believe that this chronic anthropogenic noise may disrupt the territorial and/or mating calls of males. Wisner [73] found that ambient noise can affect the frequency at which male Eastern Bluebirds (*Sialia sialis*) sing. Additionally, Bayne et al. [58] believe that this chronic anthropogenic noise may also interfere with female responses to nestling vocalizations. Leonard and Horn [74] found that nestling tree swallow (*Tachycineta bicolor*) modified their begging calls in the presence of high levels of ambient noise (65 dB(A)), with the minimum frequency increasing and the range of frequencies decreasing (although nestling growth was not affected). In an experimental study, Williams et al. [75] found that eastern bluebird and tree swallows experimentally exposed to noise from compressor stations had lower hatching and fledging success than individuals nesting in quiet boxes.

If additional land must be cleared for wells and pipelines instead of using existing well pads and right-of-ways, significant impacts to local flora and fauna are likely to occur, with both the abundance and the diversity of species in the landscape affected.

5.2. Aquatic Habitat Effects

Landscape disturbance and forest fragmentation can affect surface water quality [76]. The closer well pads, roads, and pipelines are built to streams, the higher the risk of water quality degradation, both in the stream itself and downstream. This is of particular concern in the Susquehanna River basin, where gas development is common and there is a risk to the Chesapeake Bay [76].

The impact of the withdrawal of water from surface water sources is highly dependent on the source itself. If the source is a small stream and the withdrawal is large, the impact is likely greater than a similar withdrawal volume from a large lake or river. In small streams, the withdrawal of large amounts of water may decrease dilution effects downstream, increasing contaminant concentrations, and potentially reducing water quality sufficiently to adversely affect aquatic ecosystems [77,78].

Low water levels in streams can also increase the sediment load, which may reduce populations, and decrease the general body condition and size of stream species, such as brook trout (*Salvelinus fontinalis*), which is listed as a Threatened species in Ohio [79]. Low

water levels also decrease dissolved oxygen (DO) levels, which negatively affects a variety of species. Many species of mussel are tolerant of low water levels, but elktoe (*Alasmidonta marginata*) and green floater (*Lasmigona subviridis*), both listed as Imperiled in West Virginia, are susceptible to the poorer water conditions often found during conditions of low water levels [80]. Some species of aquatic salamander require flowing water all year, and are susceptible to changes in water quality, including DO level and water temperature, which fluctuates more with low water levels. For example, the eastern hellbender (*Cryptobranchus alleganiensis*), which is Endangered in Ohio and Imperiled in West Virginia, requires cool water temperatures and is sensitive to changes in DO [80]. Reptiles that winter at the bottoms of streams and rivers often require high oxygen levels in the water to support their torpor. For example, wood turtles (*Glyptemys insculpta*), a species West Virginia lists as Vulnerable, require high DO levels in order to survive overwintering in a streambed.

Water levels in streams, rivers, and lakes naturally fluctuate throughout the year; however, the additional withdrawal of water at times when surface water sources are already naturally low or stressed can negatively impact many aquatic species, including some species of concern in the Marcellus–Utica region.

The use of surface water and landscape disturbance for hydraulic fracturing can impact surface water quality by increasing sediment loads, affecting water temperature, and changing dissolved oxygen levels. Minimizing the use of surface water can mitigate these impacts.

5.3. Waste Management Issues

Estimates of the volume of recovered flowback water (aka “produced water”) from horizontal wells in the Marcellus range from 20 to 25% of the fluid originally used to drill and fracture the well, resulting in up to 5 mil L of waste fluid to be managed [4]. Recovered flowback water is managed by a variety of methods, including: (1) injection into underground wells drilled thousands of feet deep, beyond freshwater aquifers; (2) recycling for re-fracking the well; (3) treatment on-site or at public or commercial water treatment plants; (4) evaporation ponds, with the dried material treated as solid waste; or (5) spreading on the landscape or unpaved roads [5,81]. Prior to disposition, the fluid may be stored at the well pad in tanks or open impoundments, and subsequently transported for treatment via truck or pipeline, as appropriate.

Fracking waste fluid contains sand and the original chemicals added to aid in the fracking process. In addition, as the fluid permeates the shale, salts and other inorganic and organic constituents from the rock are dissolved in the fluid. As a result, the flowback can have very high salinity, with total dissolved solids (TDS) of >200,000 ppm [81]. Another ongoing problem in evaluating the safety of produced water has been the industries’ unwillingness to reveal key details about the chemicals they put down wells, citing this information as proprietary. It is imperative, however, that they disclose not just which chemicals they use in their production, but also the volume and frequency of their use, i.e., their “recipe.” Chemicals injected under intense heat and pressure into shale beds, where they interact with scores of other compounds (including radioactive materials) before being drawn back to the surface, may change their toxicity; yet, scientists have no good tools or methods to understand what chemical interactions may occur.

In some cases, waste fluid is injected into wells deep underground, usually into limestone or sandstone formations. The wells into which the waste is injected must be protected by casings and cement linings to protect underground water sources from contamination [4]. Earthquakes up to a magnitude of 5.8 (magnitude 6 can damage even well-built structures) have been caused by the deep injected disposal of fracking waste in other basins [82], leading the Ohio EPA to revise its Underground Injection Control Program, after accepting large volumes of fluid waste from Pennsylvania and experiencing a number of lesser magnitude quakes in 2011.

The recycling of flowback water from fracking for use in future fracking operations is becoming more common. Depending on the content of the flowback water, it may need

to be treated prior to reuse [81]. For example, components with the potential to cause scaling in the well must be removed (e.g., calcium carbonate). However, even if 100% of flowback water were to be recycled, drilling and fracturing a well would still require a significant amount of freshwater to be added, because only a fraction of the flowback water is recovered from wells.

In regions with lower precipitation, such as Texas, flowback water can be pumped from the well into onsite evaporation pits. The water is allowed to evaporate and the remaining concentrated contaminants are managed as solid waste. In the Marcellus region, however, evaporation ponds are not as effective, as the evaporation rate is lower than the precipitation rate [83]. If these pits are used for flowback water or for drilling mud, they can be hazardous to wildlife [84]. Birds mistake them for fresh water and other animals are attracted to insects that become trapped in the fluid. Some of the chemicals commonly used in hydraulic fracturing can be toxic, and others, such as lauryl sulfate, are surfactants that can negatively affect the waterproofing of birds' feathers. Without proper waterproofing, birds cannot regulate their body temperature and can die from hypothermia [85].

Flowback water that is not injected, recycled, or applied to the surface is treated at public or commercial waste facilities, and released into sewage systems or surface water sources [86]. Some of these waste treatment facilities are exempt from limits on the discharge of total dissolved solids and other components of hydraulic fracturing flowback waste fluid. For example, Pennsylvania has eight treatment facilities that are exempt from discharge limits and that have treated flowback waste [86]. While the total volume of flowback waste has decreased from its peak in 2009, due primarily to the increase in recycling the fluid, waste discharged from exempt facilities into surface water sources does increase the concentrations of TDS and bromide [87]. Increased salinity in freshwater ecosystems can decrease biodiversity [88]. Given the high number of aquatic species of concern in the Marcellus–Utica region, the impact of decreasing biodiversity within surface waters could be correspondingly high.

The appropriate management of recovered flowback water is critical to prevent environmental contamination. Recycling as much as possible reduces flowback in the waste stream and the amount of fresh water required for fracturing new wells, increasing the sustainability of using water to fracture wells.

5.4. Reclamation

Ideally, when operations are completed at a well site, the site would be restored to its original condition, with intact habitats. Since much of the land cleared within the Marcellus–Utica region was originally mature forest, this level of reclamation is not considered feasible. Reclamation will generally include removing roads, re-grading the land to reduce soil erosion, restoring topsoil, and revegetating. Reclamation can occur in stages, with the removal of equipment and most of the well pad at the completion of drilling/fracturing, and the rest (removal of access roads, plugging the well, etc.) when the well's productive lifespan is complete [89].

All states in the Marcellus–Utica region require that abandoned wells must be plugged, and any pits on the site must be filled, but they generally do not regulate exactly how the sites are restored. For example, in Pennsylvania, operators are required to plant perennial vegetation to prevent erosion, but they are not required to plant native species [90]. Nor are they required to remove concrete or gravel used at the well pad itself, which could directly impact the plant species that may revegetate the site. Additionally, operators are not required to remove any invasive species that may have been established at the site during the drilling, fracturing, or production stages, which can impede revegetation with native species and adversely impact the abundance and diversity of a variety of wildlife species [91,92].

Reclamation is one step in the hydraulic fracturing process that can be carried out sustainably. Land that was originally forest can be replanted with new forest, and grassland can be restored to native grasses.

6. Discussion and Recommendations

The future of natural gas development is highly dependent on the price of natural gas and the development of other renewable energy sources, such as solar and wind. The profitability of hydraulic fracturing and horizontal drilling, which are costlier techniques than conventional drilling, decreases as the price of natural gas decreases. The price of natural gas decreases as increased production increases the supply. It is a difficult balance to predict. The price of natural gas has remained relatively stable over the last decade, with a decrease and subsequent increase during the COVID-19 pandemic (Figure 4). Demand for new well permits has steadily decreased in the Marcellus Basin (Figure 3), but new wells have become more productive than legacy wells, so total natural gas production continues to increase [93].

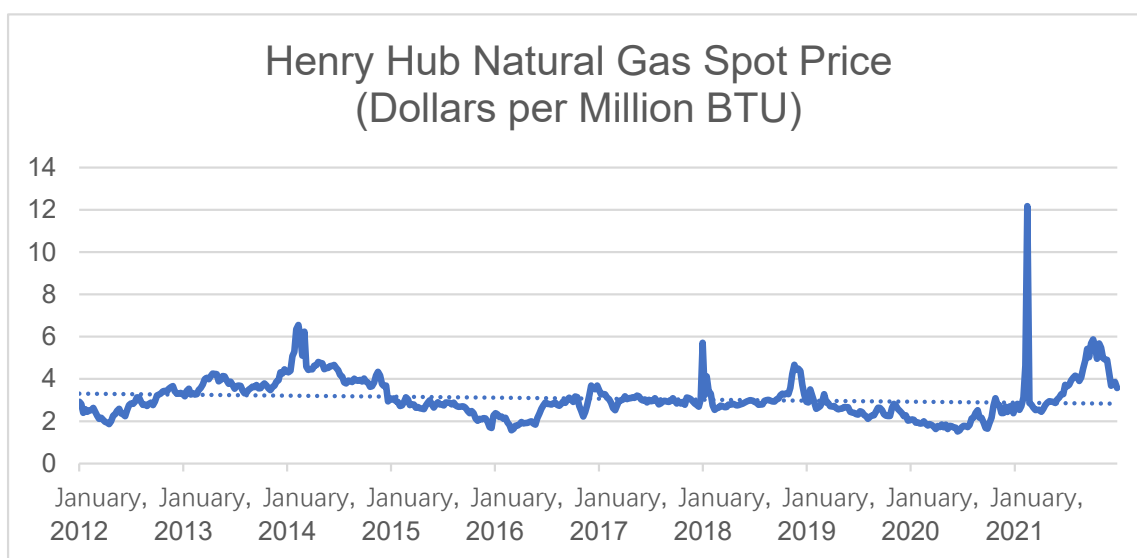


Figure 4. Henry Hub natural gas spot price (dollars per million BTU). (Source: United States Energy Information Administration).

It bears repeating that the shale gas industry has and will likely continue to exhibit an inherent “boom and bust” nature, eventually following much the same trajectory as other finite resources (e.g., anthracite coal). As the resource is gradually depleted and/or loses its profitability—the latter perhaps expedited by the successful development of other energy sources, such as solar, wind, wave, and perhaps even fusion—millions of kilometers of old pipelines, millions of spent wells, and other infrastructure may be left to deteriorate in place, without being cleaned-up or repurposed.

Natural gas development technology has outpaced regulation. The original gas and oil drilling regulation was not intended to regulate horizontal wells or hydraulic fracturing technology. Legislators of the late 19th century or the early–mid-20th century did not anticipate the large volumes of water required, the large volumes of wastewater produced, or the myriad chemicals used in the fracturing process. Early fracturing was performed under existing regulations, with regulators attempting to apply those original rules to the new process. Leaseholders were not aware of the impacts fracturing could potentially have on their properties, or the lack of probity on the part of some producers [34,94,95].

Industry, scientists, non-governmental organizations, mineral rights holders, landowners, and regulators need to develop and follow practices that represent the best knowledge available. One way to engage all parties and ensure that all perspectives are considered is to use Structured Decision Making (SDM) [96], a process for decision making and risk analysis that involves a cycle of defining the problem, stating the desired objectives, and identifying alternatives available to achieve the objectives and potential consequences for each alternative. It requires evaluating potentially conflicting objectives for tradeoffs and

optimizing the alternatives, prior to making the decision and acting on the chosen alternative. In the case of natural gas development, all the parties with an interest in the outcome must assess the process from all perspectives—the energy and economic potentials, as well as the environmental and wildlife impacts—to allow for the best possible practices to be followed. These best management practices will provide operators a clear set of guidelines when developing a well in order to minimize the negative impacts on the local ecosystems, while still allowing for gas production.

In determining the best practices, stakeholders involved in SDM must consider a commons-based approach. The commons are the natural resources that are accessible to and used by all members of society, such as the air, water, and natural habitats [97]. Because they are common goods, no one has the right to exploit them to the detriment of others. Using natural resources, such as water and forests, must be done in such a way as to preserve them for others and for future generations, as much as possible. Environmental impacts must be weighed against economic ones and managed in a sustainable way, or the commons will not be preserved for the future. In an SDM framework, these are the tradeoffs that must be examined and reconciled.

Hydraulic fracturing for natural gas is inherently an unsustainable practice, as natural gas is a finite resource; however, its negative impacts can be ameliorated with changes in the process and the development of best practices. For some practices, gas operators have already made beneficial changes on their own. Flowback fluid is more routinely re-used to fracture other wells or to refracture the original well [4]. This reduces the volume of fresh water required in the fracturing process. It also reduces costs for the operator, both for freshwater withdrawal and for wastewater disposal. Additionally, operators increasingly drill multiple horizontal wells on a single, albeit often larger, well pad, making fracking more efficient and profitable. This practice also minimizes landscape disturbance (including the creation of landscape edges), a beneficial side effect for the local flora and fauna.

Most changes, however, will need to be equally enforced through legislation or regulation, either because changes are costly or because operators feel that implementing them puts them at a competitive disadvantage. For example, during reclamation, operators are required to replant the disturbed area to provide erosion control; yet most jurisdictions do not specify how the site is to be replanted (e.g., whether native or non-native plantings are to be used, or whether the site is to be planted with grasses or mixed plantings of grasses, shrubs, and trees). For an operator with cost as the driving force, spreading non-native grass seed is the cheapest choice. While native plantings provide the most effective means of restoring a natural ecosystem in the disturbed area, without regulatory pressure, operators will have difficulty justifying the additional cost for reclamation activities, since both native and non-native plantings will fulfill the goal of erosion control. Regulators need to consider the goal of reclamation to be habitat restoration, not just the prevention of further damage by preventing further erosion.

In some cases, best management practices need to be closely managed at a regional level. For example, water withdrawal and/or water quality issues are currently regulated and enforced in some areas at the watershed level. The Delaware River Basin Commission regulates both water withdrawal and water quality [98]. The Susquehanna River Basin Commission regulates water withdrawal [99]. Within the Ohio River Basin, however, there is no similar watershed-level regulatory body providing mandates, so regulation is left to the individual six states through which the river runs (Pennsylvania, Ohio, West Virginia, Kentucky, Indiana, and Illinois); thus, there is no enforceable way to address problems at the watershed level, and decisions made by a state upstream could adversely affect a state downstream. The Ohio River—long recognized as one of the most polluted rivers in the U.S. [100]—given its relatively substantial discharge/flow, still provides habitat for many threatened and endangered species, and needs careful monitoring to protect those species. While the Ohio River Valley Water Sanitation Commission (ORSANCO), established in 1948, ostensibly still serves as an interstate water pollution control agency for the Ohio River basin, its impact on regulating water quality has been inconsistent [101,102],

and in 2019 ORSANCO voted to return oversight to the individual state governments, functionally disregarding the need for regional cooperation for environmental protection and its enforcement.

7. Conclusions

Hydraulic fracturing is a complex issue of energy production, economic costs and benefits, and environmental degradation. In this paper, we have argued that when assessing future decisions to extract natural gas, an E3 analysis must be considered to evaluate the quantitative and qualitative benefits and costs of the extraction process for society and the environment. While such E3 analyses are commonplace [103], they often ignore a commons-based approach that recognizes wildlife as an integral component of the public trust, and that a loss of biodiversity and wildlife populations can have a negative effect on ecosystem function. Because negative ecosystem impacts encompass regional interactions, energy planners should also include regional and diverse stakeholders and not rely on a narrow constituent base at the local or state level. Finally, because the dynamics of natural gas extraction are market-based, the secondary environmental impacts can vary wildly. Therefore, planners should also establish best management practices that fundamentally incorporate structured decision making to ensure that management solutions to protect wildlife and environmental quality can be sufficiently flexible to address the changing market.

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