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Assessment of policies to reduce core forest fragmentation from Marcellus shale development in Pennsylvania

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ABSTRACT

Marcellus Shale development is occurring rapidly and relatively unconstrained across Pennsylvania (PA). Through 2013, over 7400 unconventional wells had been drilled in the Commonwealth. Well pads, access roads, and gathering lines fragment forestland resulting in irreversible alterations to the forest ecosystem. Changes in forest quantity, composition, and structural pattern can result in increased predation, brood parasitism, altered light, wind, and noise intensity, and spread of invasive species. These fragmentation effects pose a risk to PA's rich biodiversity. This study projects the structure of future alternative pathways for Marcellus shale development and quantifies the potential ecological impact of future drilling using a core forest region of Bradford County, PA. Modeling presented here suggests that future development could cause the level of fragmentation in the study area to more than double throughout the lifetime of gas development. Specifically, gathering lines are responsible for approximately 94% of the incremental fragmentation in the core forest study region. However, by requiring gathering lines to follow pre-existing road routes in forested regions, shale resources can be exploited to their full potential, while essentially preventing any further fragmentation from occurring across the core forested landscape of Bradford County. In the study region, assuming an estimated ultimate recovery (EUR) of 1–3 billion cubic feet (Bcf) per well, this policy could be implemented for a minimal incremental economic investment of approximately $0.005–$0.02 per Mcf of natural gas produced over the modeled traditional gathering line development.

1. Introduction

Pennsylvania (PA) has a rich history of oil and gas development. Over 350,000 wells have been drilled in the Commonwealth since the first successful oil well in 1859 (PA DEP, 2011). Prior to 2008, wells targeted conventional gas, coal bed methane, and PA grade crude oil. In December 2007, the oil and gas production company Range Resources announced the use of horizontal drilling combined with hydraulic fracturing to successfully complete five unconventional wells (MSAC, 2011). This demonstrated the economic viability of using this combination of technologies to extract Marcellus shale gas. In 2008, Marcellus shale permits rose from 76 to 476, and between 2009 and 2010, permit applications again increased by 67% (MSAC, 2011). This general trend has continued, and through 2013 over 7400 unconventional wells had been drilled in Pennsylvania (PA DEP, 2014).

The Marcellus is the most expansive shale gas play in the United States (Kargbo et al., 2010), covering 14–25 million hectares (ha) (35–62 million acres) at a depth of 600–3000 m (Slonecker et al., 2012). The economically viable region of the Marcellus crosses southern New York, much of Pennsylvania, northern West Virginia, and eastern Ohio. Because of the continuous nature and vast expanse of the shale deposit, developers have some flexibility in locating wells. Currently in PA the vast majority of well pads are drilled with little consideration for land use preservation. In 2008 alone, half of the wells were developed in PA forests (Drohan et al., 2012). This destruction of core forest habitat posses a significant risk to forest ecosystem health and biodiversity. Additionally, deforestation results in an increase in impervious surface, which is a threat to stream health, the integrity of headwater watersheds, and quality of drinking water (Evans and Kiesecker, 2014).

Marcellus development has the potential to rapidly alter landscapes. The infrastructure required to drill and hydraulically fracture a well is extensive (see SI Section 1). Well pad construction involves removing topsoil, leveling and lining the area with geotextile fabric, and covering the pad with compact stone

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(DCNR, 2011). This development can span 1.2–2.8 ha (3–7 acres) (Johnson et al., 2010). Additional infrastructure such as access roads, water/wastewater storage, compressor stations, and gathering pipelines, is required to successfully develop the well and fully exploit the resource. These secondary components of the natural gas infrastructure on average require an additional 10 ha (25 acres) of land per well pad (Johnson et al., 2010, 2011). The combined footprint of unconventional natural gas development can total more than 12 ha (30 acres) for a single well pad.

When constructed in forests, infrastructure development significantly impacts the landscape. Current regulation requires Marcellus shale projects to be screened for impacts on threatened, endangered, and special concern species and resources using the Pennsylvania Natural Heritage Program's Pennsylvania Natural Diversity Inventory Environmental Review Tool (Henderson, 2012). While this protects the immediate habitat of specialized endangered species, it fails to consider the broad cumulative indirect impacts accrued from isolated land use changes within the core forest. This cumulative impact, rather than the localized disturbance, is a source of risk to PA's forest ecosystems.

Forest covers approximately 6.5 million ha (65%) of PA and is concentrated in the central and north central parts of the state (Slonecker et al., 2012). Large contiguous patches of core forest in these regions maintain the majority of flora and fauna species richness and diversity in the state and are critical components of the global ecosystem. More than 71 species of birds, 43 species of mammals, and 48 species of reptiles and amphibians rely on PA forests for essential habitat (Bishop, 2008). In particular, PA core forests have rare bird populations that include the bald eagle, peregrine falcon, and interior-nesting warblers (Johnson et al., 2010). For some species PA is fundamental to their global survival; more than 19% of the global population of scarlet tanagers and 9% of the global population of wood thrush breed within PA forests (Brittingham, 2011).

While pure habitat loss alone can have an adverse effect on biodiversity, ecologists note that the pattern of habitat loss is often more important than the quantity of loss. In landscape ecology, a landscape is defined as a mosaic of habitat and non-habitat patches (Swift and Hannon, 2010). The spatial relationship between habitat patches within the mosaic influences the presence, movement, and persistence of species. Anthropogenic activities can compromise the structural and functional integrity of the landscape and impede ecological flows across the habitat (Lele et al., 2008; McGarigal, 2013). When contiguous core habitats are fragmented into smaller patches, many sensitive species are unable or unwilling to cross non-habitat regions to reach these alternative habitat patches. While habitat loss can have an immediate impact on wildlife population, the ecological response to fragmentation is lagged, and affects different species at varying time scales (Makki et al., 2013).

A secondary impact of fragmentation is the creation of edges. Edges are generally defined as the 100 m between core forest and non-forest habitat (PA DEP, 2014; Kargbo et al., 2010; Johnson et al., 2010). New edges affect the physical or biological conditions at the ecosystem boundary and within adjacent ecosystems (Fischer and Lindenmayer, 2007). Edge effects are believed to be detrimental by increasing predation, changing lighting and humidity, and increasing the presence of invasive species (Johnson et al., 2010). In particular, songbirds nesting near edges and openings are less likely to successfully raise young than individuals nesting in interior forest (Brittingham, 2011). While 100 m is commonly cited as the estimated depth of edge effect penetration (Drohan et al., 2012; Johnson et al., 2010), the impact on specific species can be seen at much greater distances. In a meta-analysis of the effects of roads, power lines, and wind turbines on birds and mammals, bird populations were reduced as far away as 1 km and mammal populations at 5 km (Benítez-López et al., 2010).

In order to quantify changes induced by fragmentation, ecologists use landscape metrics. Generally, landscape metrics quantify specific spatial characteristics of patches, classes of patches, or entire landscape mosaics (McGarigal, 2013). Structural metrics measure the physical composition or configuration of the patch mosaic without explicit reference to ecological processes (McGarigal, 2013). Structural metrics are based on the theory of Island Biogeography, which interprets disjoint patches as analogous to oceanic islands embedded in an inhospitable or ecologically neutral background (MacArthur, 1967). While this is an oversimplification of how species interact with the surrounding landscape (McGarigal, 2013), it provides a useful structure for tracking habitat pattern changes in a non-species specific manner and for interpreting general impacts of fragmentation. These metrics can then be interpreted by ecologists into a functional form regarding specific species needs and considerations.

This study focuses on the following landscape metrics; the number of core patches (NCP), the largest patch index (LPI), and the percent habitat available in the landscape (PLAND) (Fig. 1). NCP is a count of the number of contiguous forest regions larger than 4 ha that are greater than 100 m from a non-forest opening. Core patch metrics are important measures of fragmentation because they integrate patch size, shape, and edge effect into a single measure (McGarigal, 2013). The LPI is the percent of the total habitat that is made up by the single largest patch and is an indicator of a species' ease of movement around the landscape matrix (connectivity). PLAND is representative of the pure habitat loss associated with land use change. These metrics were chosen as proxy variables to fully describe the composition and the configuration of the landscape. The purpose of this study is to quantify changes in these metrics as a result of various future development pathways. In this paper, the metrics are used as proxies for disturbance and are considered a reflection of the ecosystem's overall health and stability. Impact on specific species or ecosystems will require more detailed studies.

The Nature Conservancy conducted an Energy Impact Assessment to quantify the potential impacts of natural gas development on habitats (Johnson et al., 2010). They first used aerial imagery to determine the spatial footprint of well pads, roads, and water storage facilities associated with 240 well pad development sites in north central and southwestern PA. They then used a machine learning tool to develop a 30 m × 30 m resolution probability map describing the likelihood of Marcellus development across PA (see Supporting Information (SI) Section 1, Fig. S1). This modeling approach, called maximum entropy, was used to find relationships between 1461 existing and permitted well pad locations and landscape variables such as Marcellus shale depth, thickness and thermal maturity, percent slope, distance to pipelines, and distance to roads (Johnson et al., 2010). This was then re-sampled to different resolutions to reflect the separation distance (based on implied lateral length) of future alternative development scenarios. Well pads were placed in order of most probable pixels to least probable pixels until the appropriate number of well pads was located (Johnson et al., 2010). The number of well pads for each scenario represents an additional 60,000 wells across the state with varying number of wells per pad. While TNC's study presents a spatially explicit model of where well pads might be developed in the future and quantifies an overall estimate of pipeline and road development in core forest, it does not project the location of future secondary infrastructure. Since secondary infrastructure can have a footprint over eight times that of the well pad itself (see SI Section 3), the spatial distribution of this secondary infrastructure across the landscape is a key component of understanding the impact of development on ecosystem services.

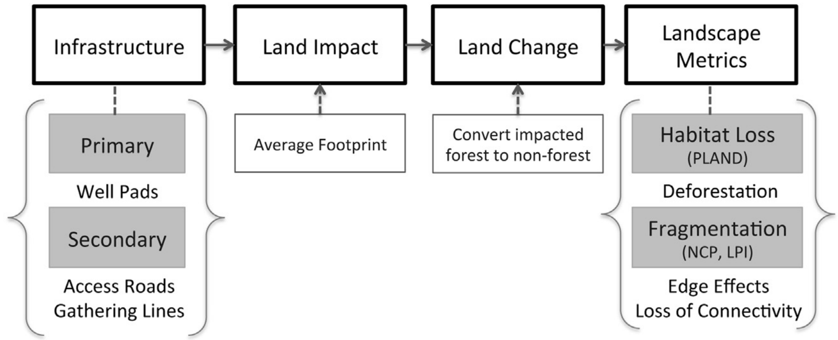

Fig. 1. The general procedure for depicting land disturbance from Marcellus shale development.

This study expands on TNC projections for potential future development by including spatially explicit projections of secondary infrastructure in addition to the well pads. It also further explores the impact of decreasing well pad density on fragmentation by using TNC methods to project three additional future development scenarios. By modeling the structure of future alternative development pathways for Marcellus shale well pads, access roads, and gathering lines throughout the lifetime of gas development, the study quantifies the potential ecological impact of future drilling using a core forest expanse in the southwestern portion of Bradford County, PA (northeast PA) as a case study.

2. Methods

This study expands on previous work (Drohan et al., 2012; Johnson et al., 2010; Bishop, 2008; McGunegle, 2009) by modeling the pipeline and road construction that would accompany the projected well pad development. It then uses both the primary and secondary infrastructure projections to quantify overall deforestation and land use change under various potential regulatory scenarios geared toward preserving habitat while preserving ability to produce the shale resource. For this study, total lifetime Marcellus shale production was held constant while varying well pad density. This represents alternative development pathways for achieving the total expected level of natural gas extraction throughout the lifetime of the play.

2.1. Study area

The methods for determining the impact of natural gas development on forested land were developed and assessed by conducting a case study in Bradford County, PA, which overlies a highly productive portion of the Marcellus shale play. Gas production in Bradford County was 870 billion cubic feet between 2010 and 2012 (PA DEP, 2014). The county was chosen because it has up to date records of pipeline development and is composed of about 56% forest. Specifically, the area modeled was a core forest region located in the southwestern corner of the county. The region is 35,000 ha of which 55% is public land and 91% is forest. Through 2012, 25 well pads had been developed in this region (see SI Section 4, Fig. S3). By focusing on a minimally developed forested area, the potential influence of non oil and gas development on this study is minimized.

2.2. Land change model development

Visualizing and analyzing land use change was accomplished using a spatially explicit model built in ArcGIS. This model was applied to both historical development to characterize past land change and to forecasted gathering line and road routing, allowing for a complete picture of future fragmentation. This process for simulating land use change was modeled after the United States Geological Survey (USGS) method for updating land cover maps to account for new natural gas infrastructure (Slonecker et al., 2012).

Quantifying habitat impact was a four-step process. First, the infrastructure's geospatial position was determined. For well pads this position was a single point within the study region, and for access roads and gathering lines these were polylines. Second, these identified locations were enlarged (buffered) from points and polylines to the average footprint of the infrastructure they represent. For example, the points representing well pads were enlarged to an area of 3 acres, the average footprint of a well pad. Third, the forested regions that now contain natural gas infrastructure were re-categorized as non-forest on the land use map. Finally the chosen landscape metrics, as shown in Fig. 1, were quantified.

2.3. 2000 land use data

Year 2000 was chosen as the baseline year because 99.8% of wells exploiting unconventional gas development were drilled after this year. Land disturbance in the study region prior to 2000 was considered non-Marcellus shale related. The land use data raster file was obtained from Penn State University in the format of an ESRI raster grid, a file format compatible with ArcGIS (PASDA, 2000). Because the focus of this study is solely on forest ecosystems, this raster was reclassified into two categories of land use: forest (including coniferous, mixed, and deciduous forests) and non-forest. The original resolution of the raster was 30 m × 30 m. However, some components of Marcellus shale development such as roads are too narrow to be captured at this resolution. Therefore, the raster was resampled to a 10 m × 10 m resolution and the pixels underlying PA's year 2000 road network were re-categorized from forest to non-forest (ESRI, 2013).

2.4. 2012 infrastructure

Year 2012, the most recent complete year of well location data available, was chosen to represent the current Marcellus shale development. Data on existing 2012 road network and the existing well pads were obtained from the PA Department of Environmental Protection (DEP) database (PA DEP, 2014). Roads connecting state and local roads to well pads are mostly private roads and are therefore missing from the road database. These roads were modeled as straight lines between the well pad and the nearest road in the road dataset. The lengths of the modeled roads were compared to lengths of roads constructed for Marcellus development as documented in the literature for validation (Brittingham et al., 2013) (see SI Section 5, Fig. S4). All roads were then buffered to 10 m to represent a typical footprint of a road used in Marcellus shale construction (USGS, 2011).

In Bradford County, detailed locations of gathering lines are maintained by the county's planning office. These gathering line routes developed through 2012 were compared to a theoretical shortest length gathering line network developed by the model. This was done to (1) understand the potential for reducing surface disturbance from gathering lines, and (2) to identify the ways in which the modeled theoretical future gathering lines could vary from how the industry might realistically develop in the future without regulatory guidance. This theoretical network was created by first locating the two main transmission lines in the county from a map of PA's major gas pipelines (MCOR, 2010). The modeled gathering line network was constructed by adding the 2012 well pads one at a time in order of spud date and connecting each to the nearest previously existing main transmission line or gathering line. The resulting network was manually edited to reduce the number of hook up points to the main transmission lines to more closely resemble the observed number. The final modeled gathering line network had approximately 20 hook up points as compared to 16 hookup points identified by manually searching Google Maps along the two main transmission lines running through Bradford county. Marcellus gathering lines right of ways have documented widths ranging from 10 to 46 m and main transmission lines have been measured at widths of up to 61 m (Johnson et al., 2011). Therefore, in this study the gathering lines were buffered to 15 m and the main transmission lines were buffered to 46 m to represent conservative estimates of right of ways for the two installations. The buffered well pads, roads, and gathering lines were then overlaid on the land use raster and underlying forest was re-categorized as non-forest.

2.5. Infrastructure impact

The areal extent of the well pad is often thought to be the dominant surface impact of natural gas development (Soeder et al., 2014). However, the principles of landscape ecology predict that the primary significant ecological impact will result from the linear gathering line corridors cutting through forest. To test this hypothesis, landscape metrics were calculated for disturbances from each of the three components of infrastructure individually and compared to landscape metrics resulting from the complete network of projected alternative development pathways for well pads, roads and gathering lines.

2.6. Policy scenarios

The two regulatory measures considered here for reducing the impact of natural gas development are: (1) reducing well pad density, and (2) requiring gathering lines to follow the path of pre-existing roads in forested regions. Reducing well pad density can be accomplished by increasing the number of wells per pad, and/or by elongating the laterals (Kiviat, 2013).

In this study, six different well pad densities were considered to understand the impact of regulating the spatial distribution of well pads. Three of the scenarios were developed by TNC for their Energy Impact Assessment. An implied lateral length was calculated from the study's minimum separation distance. These three scenarios had 145, 88, and 58 well pads, with corresponding implied lateral lengths of 760 m, 880 m, and 1100 m (Johnson et al., 2010). The remaining three scenarios were chosen to represent the current technological frontier in horizontal drilling (28 well pads with an implied lateral length of 2100 m) and two scenarios representing technological advancement (8 and 5 well pads in the study region with implied lateral lengths of 4300 m and 6100 m respectively). These additional three scenarios were developed according to the TNC methods. First, TNC's probability surface was resampled to raster cells with diagonals that are twice the expected lateral length. Diagonals were used to designate minimum distance between well pads because the direction of the lateral is controlled by the minimum horizontal earth stress which is oriented NNW-SSE in PA (MSAC, 2011). Next, a point was placed in the center of each raster cell and the number of points equaling the expected number of well pads with the highest probability according to the resampled probability layer were chosen as the well pad locations. Finally, each well pad was then buffered to 1.2 ha circles (radius = 62 m) to represent an average well pad footprint (see SI Section 6, Fig. S5). These six scenarios correspond to well pad densities of 48, 32, 23, 15, 9.4, and 8.6 well pads/100 km^2 (see SI Section 6, Table S1). The resampling process used to locate future development introduces variability across the scenarios in the probabilities used to identify well pad locations. This occurs because new probability values are interpolated from different cells of the original probability raster depending on the assumed lateral length for the specific scenario. To account for this uncertainty, a Monte Carlo analysis was conducted with randomized well pad placement within the probability raster cells (see Section 3.3).

The roads for each scenario were modeled as straight lines between the well pads and the existing road network as of 2012 and then buffered to 10 m. The gathering lines were modeled by connecting each well pad to the existing gathering line network one at a time in order of descending probability of future development based on the assumption that the likelihood of development is representative of a realistic construction order. These gathering lines were then buffered to 15 m. Finally, the buffered well pads, gathering lines, and roads for a given future scenario were overlaid on the derived 2012 land use raster. All raster cells underlying the infrastructure were classified as non-forest.

Policy scenario two, requiring gathering lines to follow the route of pre-existing roads, was modeled using the 32 and the 15 well pads/100 km^2 scenarios. These scenarios were chosen because they represent both a typical lateral length and an approximate maximum length achievable with current horizontal drilling technology. The gathering lines were forced to follow the path of the existing roads by using the least cost path tool in ArcGIS where existing roads were given a resistance cost of 1 and the rest of the case study region was assigned a resistance cost of 100.

3. Results and discussion

The impact of Marcellus shale development on Pennsylvania's forests is of major concern to stakeholders interested in preserving the forest ecosystem and protecting Pennsylvania's endangered species that live in core forest habitats. The results of this study describe both the landscape impact that has already occurred as a result of historical natural gas development, as well as the potential future landscape disturbance due to unmanaged future development. Finally, the study results lead to potential policy measures that could mitigate the risk of additional forest fragmentation, while simultaneously allowing for natural gas extraction.

3.1. Historical disturbance

Natural gas development over the past decade has contributed to fragmentation across all of Bradford County (Drohan et al., 2012; Johnson et al., 2010). Between 2000 and 2012, approximately 110 km of roads and 1600 km of gathering lines have been constructed to support 1080 wells. This has resulted in the loss of about 13,000 ha of core forest (including core forest lost to the creation of new edges) and an increase in the number of core patches in Bradford County from 900 to 1000 (see SI Section 7, Table S2).

This historical natural gas development has already impacted the core forest study region of Bradford County. Between 2000 and

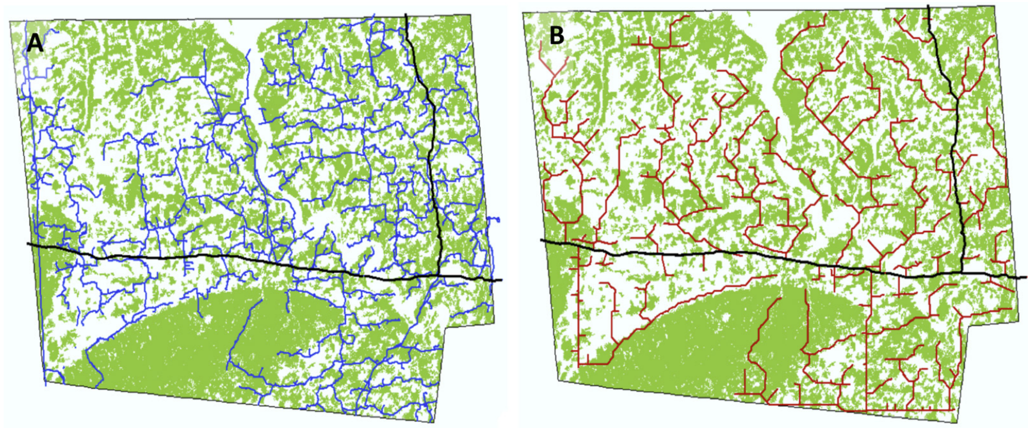

Fig. 2. Main gas line (black) and gathering line network in Bradford County (A) as built through 2012 (blue) (B) as modeled by the straight-line method (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2012, 25 well pads were developed in this area. Comparing the 2000 land use map to the 2012 land use map developed with the efficient theoretical gathering line route demonstrates that the number of core patches increased by 25% (from 65 to 81). Additionally, the single largest patch decreased from about 16% of the total habitat area to about 12% (see SI Section 7, Fig. S6).

The model developed to simulate gathering line construction prior to 2013 was based on straight-line connections between well pads and the identified main transmission lines. This strategy resulted in a 2012 gathering line network that followed a similar pattern as the actual network of gathering lines constructed in Bradford County, although qualitatively, with fewer redundancies and extraneous branches. The modeled gathering lines (Fig. 2B) totaled 900 km of pipeline across all of Bradford county versus the 1700 km of pipeline as built (Fig. 2A) (Molnar, 2013). The modeled gathering lines serve as the baseline historical development that was used as the starting point for projections for future alternative development pathways. Thus, projected fragmentation modeled here is most likely an underestimation of the potential impact. Additionally, the drastic reduction in total pipeline length between the developed and modeled infrastructure shows that there are configurations that could connect the same number of wells at the same locations with reduced pipeline development. This implies that there could be an opportunity for concomitant economic and ecological benefits.

Upon inspection, Bradford County gathering line development shows that much of the development is in rural areas in relatively level terrain and thus did not appear to be impacted specifically by topographical concerns or land use issues. While further model refinement (e.g., addition of topography, land ownership, and additional land-use categories) could modify the modeled gathering line system to more closely resemble the shape of the current network, the model would still not follow the precise patterns of the developed gathering lines in Bradford County, because the county was developed with little or no coordination by seven independent companies each trying to minimize their own costs.

3.2. Infrastructure impact results

Directional drilling has been suggested as a solution to minimize natural gas-related deforestation. By drilling multiple wells per pad, developers claim they are reducing their surface disturbance and impact. However, by isolating the three key components of infrastructure and measuring their individual contributions to fragmentation, it is clear that well pads are responsible for little incremental land disturbance (Table 1). In the forest study region, the 2012 well pads alone were responsible for increasing the number of core patches by two. Likely this increase is due to the development of new roads between 2000 and 2012 rather than the development of the well pads. The access roads in isolation contributed to four additional core patches, and finally the gathering lines in isolation were responsible for a 20% increase in the number of core patches (14 additional core patches).

When the number of well pads increases beyond the 2012 existing development by 58 well pads in the study region, a similar trend is observed. The well pads and access roads in isolation cause minimal marginal impact, whereas the gathering lines are responsible for a prominent increase in core patches from 81 to 133. Thus, policies for reducing fragmentation from natural gas development should focus on regulating gathering line development.

3.3. Policy scenario results

The two regulatory measures considered here are: (1) reducing well pad density, and (2) requiring gathering lines to follow the route of pre-existing roads. Reducing well pad density will decrease the number of well pads and reduce the number of required gathering lines. Requiring gathering lines to follow the route of roads would not reduce the quantity of gathering lines, and would likely increase the total length of the gathering lines but this would follow infrastructure that already has caused fragmentation. The important implication of this policy is that the location of the gathering lines would be regulated so as to not create new corridors across the core forest.

In the core forest study region, limiting well pad density results in the creation of fewer additional core patches. Furthermore, as well pad density decreases, the size of the core patches increases (Fig. 3). Assuming the baseline year 2000, fragmentation from

Table 1
The isolated incremental impact of well pads, access roads, and gathering lines for 2012 and the 58 well pad scenario.

Development scenario	Number of core patches (#)	Largest patch (%)
2000 (no development)	65	16
2012 well pads	67	16
2012 access roads	69	16
2012 modeled gathering line	79	13
Total 2012 development	81	12
58 projected well pads	81	12
Projected access roads	85	12
Projected gathering lines	133	10
Projected total future impact	151	9

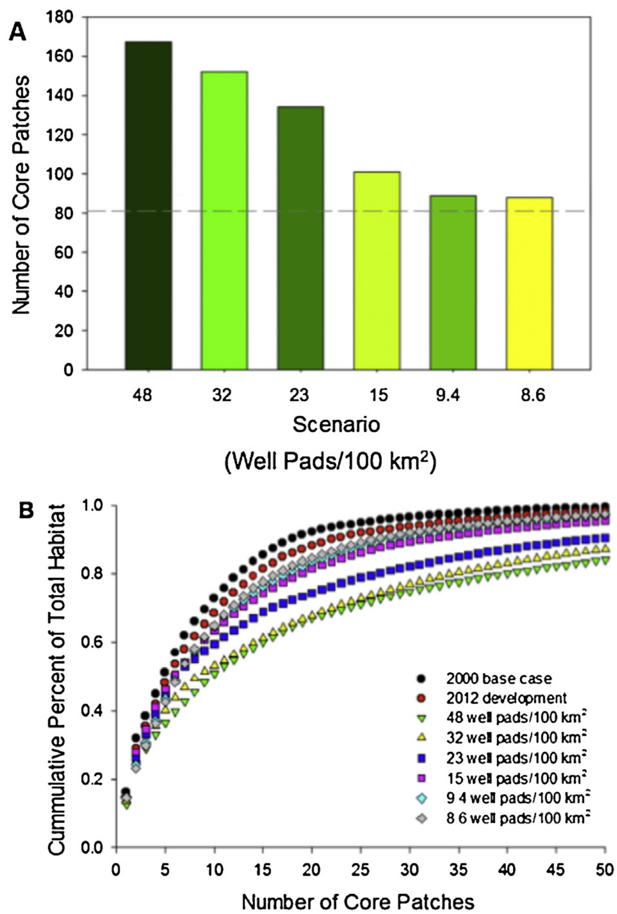

Fig. 3. As the well pad density decreases (A) the total number of core patches decreases and (B) the area of each core patch remains larger.

Marcellus shale development through 2012 has increased the number of core patches by 25%. If left unchecked, future development could further increase the number of core patches from 81 in 2012 to 167 throughout the lifetime of the play. This would be a 100% increase above the 2012 level of fragmentation. Similarly, the LPI (largest patch index) and PLAND (total percent habitat) decrease as lateral lengths decreases. Because LPI and PLAND are indicators of fragmentation, the decreasing metrics signify that additional fragmentation is projected to occur (see SI Section 8, Fig. S6).

Horizontal drilling technology is currently capable of achieving laterals approximately 3000 m long. Therefore, the minimum achievable density is about 15 well pads/100 km^2. This would still result in an increase in the number of core patches from 81 to 101 core patches, or a 25% increase above 2012 levels. The results show that even with a significant advancement in technology resulting in laterals over twice as long as currently feasible, 2012 levels of fragmentation cannot be maintained by decreasing well pad density alone.

The results of the policy alternative of requiring all gathering lines to follow the route of pre-existing roads (See SI Section 9, Fig. S8) show that this policy essentially maintains fragmentation at the 2012 level regardless of well pad density. For example, in the 15 well pads/100 km^2 scenario, the model indicates that the number of core patches in the study region increases by one when the gathering lines follow the route of pre-existing roads, as opposed to the incremental 20 patches projected by the straight line gathering line model. Additionally, as shown in Fig. 4, the distribution of core patch area is maintained at the 2012 level in addition to the number of core patches.

Uncertainty analysis to determine the sensitivity of these policy scenario results to variations in projected well pad location within a given scenario was conducted using a spatially explicit Monte Carlo simulation. The original TNC method for well pad placement assumes that the well pads will be located in the center of the cells from the re-sampled probability surface map. This simulation was done to explore how the results change when well pads were instead allowed to be located randomly within the cell, given that the minimum separation distance is still observed. While the metrics do vary depending on where the well pads are located, the results of the Monte Carlo simulation confirm that there is a distinct difference in the average level of landscape disturbance across the scenarios despite the uncertainty in exact well pad placement (see SI Section 10). While fragmentation would increase beyond 2012 levels in all six scenarios, encouraging a decrease in well pad density via increased lateral length can have a small but positive impact on ecological conservation. Furthermore, increasing lateral length reduces the uncertainty in fragmentation impacts to the landscape. These results support the best practices as outlined in the literature (Bearer et al., 2012) and as designated by the PA DNCR (PA DCNR, 2013) that suggest careful consideration of well pad location prior to development can be a productive measure in reducing the impact of Marcellus shale surface disturbance.

This study demonstrates that Marcellus shale development has caused and will continue to cause further ecological disturbances in Bradford County's largest region of contiguous core forest if left unregulated. While the numerical results of this study are specific to the forested case study region within Bradford County, the observed trends and conclusions could be extended to the Commonwealth of Pennsylvania as a whole, across the United States, and globally using these techniques and approaches. Although there may be differences in the types of land cover and the degree of development, it is likely that the shale gas development will proceed rapidly and follow a spatial pattern dependent on the resources' potential and not constraints of the landscape, its cover, or ecosystem value (Drohan et al., 2012).

While minimizing well pad density provides localized habitat conservation benefits, based on the analysis of the impact of each component of infrastructure in isolation, it is apparent that gathering lines are the single largest contributor to large-scale forest fragmentation from natural gas development. As a result, regulatory measures seeking to minimize the land use impact of Marcellus development on core forest should target gathering line routing practices. Specifically, using the core forest region in Bradford County as a case study, we find that requiring gathering lines to follow the route of pre-existing roads within the core forest region would successfully prevent additional fragmentation.

Successful implementation of such a gathering line siting regulation within a forest region would require both that the land be available for development and gathering line construction be coordinated among operators. These two constraints could be addressed through compulsory pooling and unitization laws. Compulsory pooling mandates that a landowner lease his land if a threshold percentage of neighboring land has been leased. Unitization requires a single operator to be responsible for coordinated development of gathering lines to all well pads in a given region. In addition to eliminating gathering line redundancies and reducing fragmentation, unitization would economically benefit developers; the 2012 modeled gathering lines in this study is representative of a unified development approach and demonstrates that the total length of gathering lines necessary to reach all well pads in Bradford County could have been reduced by almost half (from 1700 km to 900 km) had unitization been historically required. This reduction in gathering line length is significant, given the average cost of $1–$1.5 M per mile of pipeline (Henderson, 2012). Furthermore, because developers can range from multinational corporations to

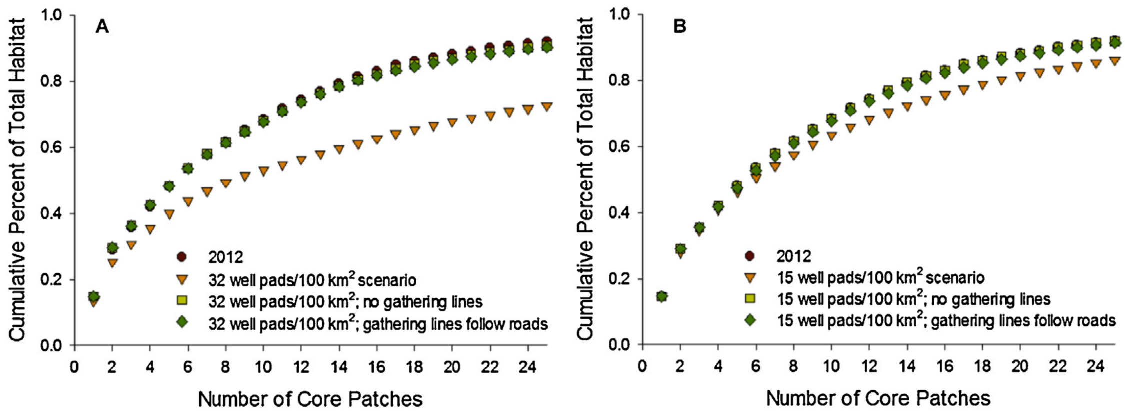

Fig. 4. Policy scenario two compared to the (A) 32 well pads/100 km^2 scenario and (B) 15 well pads/100 km^2 scenario with and without gathering lines.

small family owned operators, a significant challenge in regulating shale gas production has historically been the wide range in the abilities of actors in the industry to adhere to new regulatory requirements (Konschnik and Boling, 2014). Unitization would overcome this challenge by forcing all developers to contribute proportionally to cooperative gathering line siting.

Compulsory pooling and unitization are already established in Pennsylvania through the Oil and Gas Conservation Law of 1961. However, as written, this law applies only to well bores that penetrate the Onondaga Horizon, thus Marcellus wells are currently exempt (MSAC, 2011). Because future natural gas development in Pennsylvania is likely to be primarily from shallower well bores targeted at the Marcellus shale play, this law should be amended to include compulsory pooling and unitization for Marcellus wells in support of gathering line siting policies. Successful implementation of these policies would also require a clear plan for obtaining funding to enforce the rules and appropriately address violations to ensure remediation and dis-incentivize future violations (Wiseman, 2014).

In further support of compulsory pooling and unitization, Pennsylvania should adopt a requirement of comprehensive drilling plans (CDP) for the unit. CDPs are currently voluntary in Colorado and are being considered as a best management practice in Maryland. A CDP requires an operator to outline all aspects of any foreseeable future development (including resource protection, environmental monitoring, gas transmission plans, etc.) in a given geographic region. This would allow developers to work together to create an integrated plan for efficient development (Eshleman and Elmore, 2013). By carefully mapping the "constraints" on gas development presented by a variety of environmental and socio-economic factors and by identifying the foreseeable oil and gas activities in a defined geographic area upfront, energy companies working cooperatively with other stakeholders (including state natural resource agencies) can exploit the resource while minimizing impacts on local communities, ecosystems, and other natural resources.

Political economists believe that states might choose to minimize governmental interference out of fear of driving away developers, thereby pursuing short term economic gain over long term risk management (Rabe, 2014). Although gathering line siting regulations would increase the economic investment required by developers, over the lifetime of the play the incremental investment would be trivial. In the 15 well pads/100 km^2 scenario modeled here, the total length of the gathering line network would increase by 4 km over the efficient 2012 gathering line network (from 96 to 100 km) within the core forest region. At an estimate of \$1–\$1.5 M per mile of gathering line (Henderson, 2012), this regulation might cost an additional \$2.4–\$3.6 M over non-restricted gathering line development in the core forest case study region. Given an estimated ultimate recovery (EUR) of 1–3 billion cubic feet (Bcf) per well (Laurenzi and Jersey, 2013; Jackson et al., 2014; Jiang et al., 2011), for this scenario of 28 additional well pads and assuming an average of 6 wells per pad, this translates into an investment of approximately \$0.005–\$0.022 per Mcf of natural gas produced (see SI Section 11). The minimal cost is more than offset by a more optimal development scenario and allows for preserving the delicate pattern and structure of contiguous core forest habitat while allowing private industry to engage in development and to exploit the resource.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.11.031.

References

Bearer, S., Nicholas, E., Gagnolet, T., DePhilip, M., Moberg, T., Johnson, N., 2012. Evaluating the scientific support of conservation best management practices for shale gas extraction in the Appalachian Basin. Environ. Pract., 308–319.

Benítez-López, A., Alkemade, R., Verweij, P.A., 2010. The impacts of roads and other infrastructure on mammal and bird populations: a meta-analysis. Biol. Conserv. 143 (6), 1307–1316.

Bishop, J., 2008. Temporal Dynamics of Forest Patch Size Distribution and Fragmentation of Habitat Types in Pennsylvania. The Pennsylvania State University.

Brittingham, M., 2011. Habitat Fragmentation. http://www.marcellusfieldguide.org/index.php/guide/ecological_concepts/habitat_fragmentation/ (accessed 10/2013).

Brittingham, M., Drohan, P., Bishop, J., 2013. Initial Landscape Changes Associated with Marcellus Shale Development; Implications for Forests and Wildlife , 18th Central Hardwood Forest Conference.

Department of Conservation and Natural Resources (DCNR), 2011. Guidelines for Administering Oil and Gas Activity on State Forest Lands. Bureau of Forestry.

Drohan, P.J., Brittingham, M., Bishop, J., Yoder, K., 2012. Early trends in landcover change and forest fragmentation due to shale-gas development in Pennsylvania: a potential outcome for the Northcentral Appalachians. Environ. Manage. 49 (5), 1061–1075.
Eshleman, K.N., Elmore, A., 2013. Recommended Best Management Practices for Marcellus Shale Gas Development in Maryland. Appalachian Laboratory.
ESRI, Census 2000 TIGER/Line Data, 2013. http://arcdata.esri.com/data/tiger2000/tiger_county.cfm?sfips=42 (accessed 10/2013).
Evans, J.S., Kiesecker, J.M., 2014. Shale gas, wind and water: assessing the potential cumulative impacts of energy development on ecosystem services within the Marcellus play. PLOS ONE 9 (2), e89210.
Fischer, J., Lindenmayer, D.B., 2007. Landscape modification and habitat fragmentation: a synthesis. Global Ecol. Biogeogr. 16, 265–280.
Governor's Marcellus Shale Advisory Commission (MSAC), 2011. http://files.dep.state.pa.us/PublicParticipation/MarcellusShaleAdvisoryCommission/MarcellusShaleAdvisoryPortalFiles/MSAC_Final_Report.pdf (accessed 10/2013).
Henderson, P., 2012. Report to General Assembly on Natural Gas Gathering Lines. http://files.dep.state.pa.us/OilGas/BOGM/BOGMPortalFiles/Act13/Pipeline-PlacementReport/FINAL_REPORT.pdf
Jackson, R.B., Vengosh, A., Carey, J.W., Davies, R.J., Darrah, T.H., O'Sullivan, F., Pétron, G., 2014. The environmental costs and benefits of fracking. Annu. Rev. Environ. Resour. 39 (1), 327–362.
Jiang, M., Griffin, W.M., Hendrickson, C., Jaramillo, P., VanBriesen, J., Venkatesh, A., 2011. Life cycle greenhouse gas emissions of Marcellus shale gas. Environ. Res. Lett. 6 (3), 034014.
Johnson, N., Gagnolet, T., Ralls, R., Zimmerman, E., Eichelberger, B., Tracey, C., Kreitler, G., Orndorff, S., Tomlinson, J., Bearer, S., Sargent, S., 2010. Pennsylvania Energy Impacts Assessment. The Nature Conservancy.
Johnson, N., Gagnolet, T., Ralls, R., Stevens, J., 2011. Natural Gas Pipelines. The Nature Conservancy.
Kargbo, D.M., Wilhelm, R.G., Campbell, D.J., 2010. Natural gas plays in the Marcellus shale: challenges and potential opportunities. Environ. Sci. Technol. 44 (15).
Kiviat, E., 2013. Risks to biodiversity from hydraulic fracturing for natural gas in the Marcellus and Utica shales. Ann. N. Y. Acad. Sci. 1286, 1–14.
Konschnik, K.E., Boling, M.K., 2014. Shale gas development: a smart regulation framework. Environ. Sci. Technol. 48 (15), 8404–8416.
Laurenzi, I.J., Jersey, G.R., 2013. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas. Environ. Sci. Technol. 47 (9), 4896–4903.
Lele, N., Joshi, P.K., Agrawal, S.P., 2008. Assessing forest fragmentation in northeastern region (NER) of India using landscape matrices. Ecol. Indic. 8 (5), 657–663.
MacArthur, R.H., 1967. The Theory of Island Biogeography, vol. 1. Princeton University Press.
Makki, T., Fakheran, S., Moradi, H., Iravani, M., Senn, J., 2013. Landscape-scale impacts of transportation infrastructure on spatial dynamics of two vulnerable ungulate species in Ghamishloo Wildlife Refuge, Iran. Ecol. Indic. 31, 6–14.
Marcellus Center for Outreach & Research (MCOR), 2010 http://www.marcellus.psu.edu/resources/maps.php (accessed 10/2013).
McGarigal, K., 2013. Landscape pattern metrics. In: Encyclopedia of Environmetrics. John Wiley & Sons, Ltd.
McGunegle, M., 2009. The Effects of Oil and Gas Development on Forest Fragmentation and Breeding Bird Populations in the Allegheny National Forest. The Pennsylvania State University.
Molnar, S., 2013. Bradford County Gas Lines. Bradford County Planning and Grants (personal communication).
Pennsylvania Department of Environmental Protection (PA DEP), Oil and Gas Well Drilling and Production, 2011. https://thompson.house.gov/sites/thompson.house.gov/files/PA%20DEP%20Oil%20and%20Gas%20Well%20Drilling%20and%20Production.pdf (accessed 10/2013).
Pennsylvania Department of Conservation and Natural Resources (PA DCNR), Shale Gas Development and State Forests, 2013. http://www.dcnr.state.pa.us/cs/groups/public/documents/document/dcnr_017270.pdf (accessed 10/2013).
Pennsylvania Department of Environmental Protection (PA DEP), Spud External Data, 2014. http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/Spud_External_Data
Pennsylvania Spatial Data Access (PASDA), Pennsylvania Land Cover, 2000. http://www.pasda.psu.edu/uci/FullMetadataDisplay.aspx?file=palanduse2000.xml (accessed 10/2013).
Rabe, B.G., 2014. Shale play politics: the intergovernmental Odyssey of American shale governance. Environ. Sci. Technol. 48 (15), 8369–8375.
Slonecker, E.T., Milheim, L.E., Roig-Silva, C.M., Malizia, A.R., Marr, D.A., Fisher, G.B., 2012. Landscape Consequences of Natural Gas Extraction in Bradford and Washington Counties. U.S. Department of the Interior/U.S. Geological Survey.
Soeder, D.J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A., Capo, R., 2014. An approach for assessing engineering risk from shale gas wells in the United States. Int. J. Coal Geol. 126, 4–19.
Swift, T.L., Hannon, S.J., 2010. Critical thresholds associated with habitat loss: a review of the concepts, evidence, and applications. Biol. Rev. Camb. Philos. Soc. 85 (1), 35–53.
United States Geological Survey (USGS), 2011. Reasonably Foreseeable Development Scenario for Oil and Gas for the George Washington National Forest Virginia and West Virginia. U.S. Department of the Interior.
Wiseman, H., 2014. The capacity of state institutions to govern shale gas development risks. Environ. Sci. Technol. 48 (15), 8376–8387.