Land Cover Change Associated with Unconventional Oil and Gas Development in the Appalachian Region

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Abstract

Unconventional oil and gas (UOG) wells from the Marcellus and Utica shale plays have expanded greatly across the Appalachian region of the United States (US) since the early 2000s. This region is now the single largest natural gas producing area of the US. The local and regional impacts of this industry on the landscape make it critical to understand for future planning efforts. This study investigated land cover change associated with over 21,000 unconventional wells representing 4,240 well pads permitted from 2007 to 2017 in Pennsylvania, West Virginia, and Ohio. The goal was to characterize UOG disturbance to document development patterns and extents in the region. Supervised classification was used to map land use and land-cover changes within a 25-ha buffer of well pads identified in the region. On average, disturbance related to unconventional development impacted 6.2 ha in Pennsylvania, 4.7 ha in Ohio and 4.4 ha in West Virginia and 5.6 ha over the region. Forest and grassland were found to be the most impacted cover types, with increases in impervious surface areas being a significant contributor to land-use classification change. These conversions can contribute to increased forest fragmentation and edge, which can in turn adversely impact biodiversity indicators at the regional level. Additionally, increases in impervious surface in small headwater watersheds can lead to increased sediment and runoff loads in receiving streams. Local and regional land use planning should be implemented during the well pad permit review process to help minimize environmental impacts over larger geographic scales.

Keywords Unconventional oil and gas · Well pads · Image classification · Landscape change · Forest disturbance

Introduction

The Appalachian basin has become the single largest natural gas producing region in the US (U.S. Department of Energy USDOE (2020)). This is the result of the highly productive unconventional resources that are developed using horizonal well bores and hydraulic fracturing (Scanlon et al. 2017). These unconventional resources include the Utica shale play, which covers an area of 298,000 km^2, and the Marcellus shale play, which extends over 240,000 km^2 (Kargbo et al. 2010; Popova 2017a, b). These shales encompass much of Pennsylvania and West Virginia, and extend into parts of eastern Ohio, western Maryland, and southern New York (Kargbo et al. 2010) (Fig. 1). In 2019

Pennsylvania was the second largest natural gas producing state in the nation, and when combined with Ohio and West Virginia represented over 33% of the total U.S. Natural gas production (U.S. Energy Information Administration US EIA (2021)). Natural gas production from this region is expected to almost double through 2050 (U.S. Department of Energy USDOE (2020)) and will continue to be dominated by Pennsylvania, West Virginia, and Ohio because of moratoriums on drilling using hydraulic fracturing in New York and Maryland (Hastings et al. 2017; Sangaramoorthy 2018; Leff 2015).

Increased production in the region can be attributed to new technology adopted by exploration and production companies. Modern techniques involve more efficient drilling and fracking technologies, as well as an increased number of wells being drilled per well pad. Companies have also been using longer lateral well bores, which can result in greater levels of production (Izadi et al., (2014)). The increased development of these resources in the region has led to significant surface disturbance from UOG related clearing and construction. Unconventional well pads tend to

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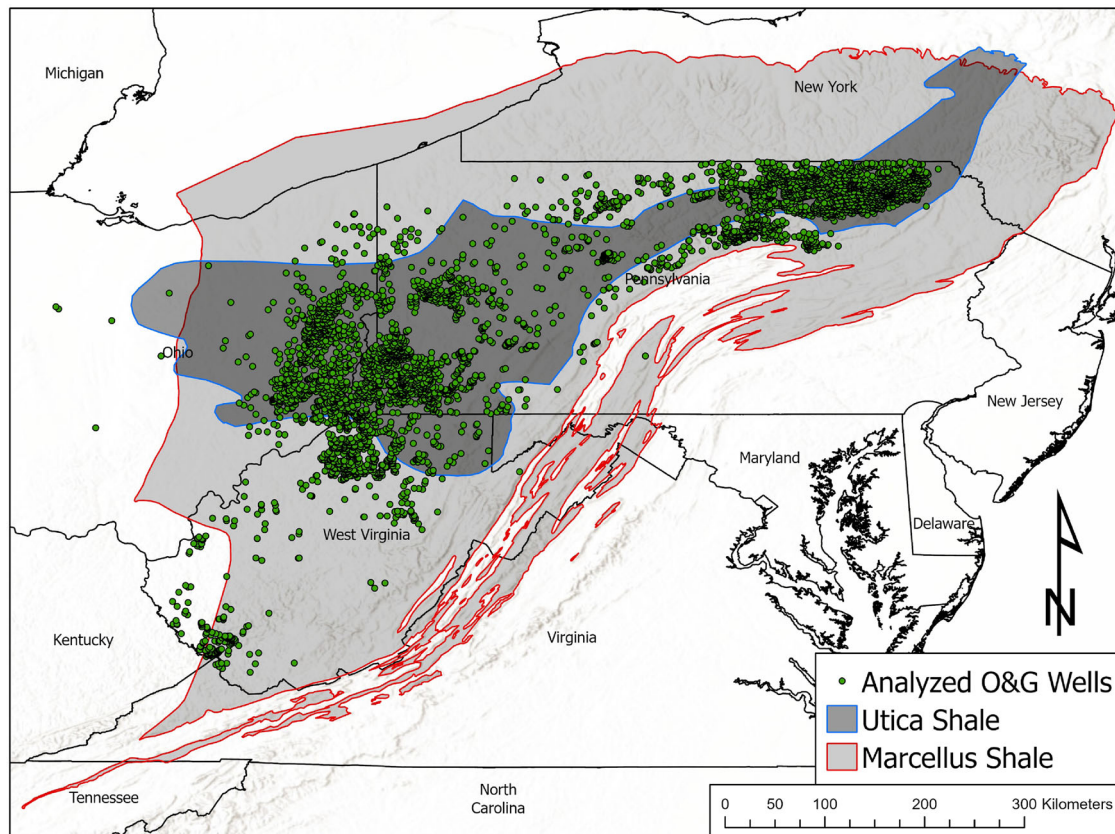
Fig. 1 Extent of the Marcellus and Utica shales in the Appalachian region (US. EIA 2016a)

be much larger than conventional wells (Slonecker and Milheim 2015) ranging from 1.2 to 4.2 hectares (Drohan and Brittingham 2012; Grushecky et al. 2022; Jantz et al. 2014; Johnson et al. 2010, Langlois et al. 2017; Liu 2021; Slonecker et al. 2012a, b; Slonecker and Milheim 2015). Additional surface impacts are attributed to access roads and tank-pads, which are built as part of the drilling process, as well as the creation of midstream infrastructure. Midstream infrastructure includes the gathering and transmission pipelines, as well as compressor stations and all other infrastructure necessary for the transportation of petroleum products. Midstream activities add between 64% (Jantz et al. 2014) and 250% (Langlois et al. 2017) to the area disturbed during well pad development.

The land disturbance due to increased petroleum exploration and production in the region have been found to be the driving force of a wide range of ecosystem impacts. Site clearing for production has led to increases in impervious surfaces and deforestation (Evans and Kiesecker 2014; Johnson et al. 2010; Young et al. 2018) with forest fragmentation being one of the most noted consequences (Drohan et al. 2012; Langlois et al. 2017). Pierre et al. (2018) concluded that, compared to urbanization and agricultural activities, energy development has a higher potential for edge effects. Associated land cover change also impacts wildlife habitats and populations, being especially true for core forest habitats (Johnson et al. 2010; Ritters et al. 2002). Biologists have noted that the shape and contiguity of forest loss has a greater impact on biodiversity than just the total area of disturbance (Abrahams et al. 2015; Johnson et al. 2010). This type of habitat loss has been shown to impact avian communities in the region (Farwell et al. 2016; Farwell et al. 2020). Aquatic environments can also be impacted by the land disturbance of shale development. This impact is increased in the Marcellus, as many well pads are located within 300 m of streams in the region (Entrekin et al. 2011). One noted consequence is the increase in total suspended solids (TSS) levels in watersheds with drilling activity (Olmstead et al. 2013).

At present, research on disturbance characteristics and ecosystem impacts of unconventional resource extraction has been based on state, county, or smaller geographic level data. The Marcellus extent in Pennsylvania has received most of the focus at the state (Drohan et al. 2012; Drohan and Brittingham 2012; Slonecker and Milheim 2015), or county levels (Donnelly et al. 2017; Jantz et al. 2014; Slonecker et al. 2012a, b; Young et al. 2018; Langlois et al. 2017). In Ohio, the only published research related to

surface disturbance is at the county (Donnelly et al. 2017) or watershed (Liu 2021) levels. As many of the previous studies have noted, it is important to study the continuing disturbance from UOG development within the Appalachian region. The objectives of this work were to document the current state of surface disturbance related to UOG development across the entire Appalachian basin production area, to gain a better understanding of cover-type disturbance in the region, and to compare and contrast this disturbance among states. This study is the first that approached the UOG disturbance in a regional extent encompassing multiple states over a ten-year period. This information can help scientists and managers understand future land conversion issues at both the local and regional levels, and orient future planning and regulatory guidance.

Material and Methods

UOG Development in the Appalachian Basin

Locations were assembled for UOG wells in Pennsylvania, West Virginia, and Ohio in the Appalachian Basin from 2007 to 2017. While shale development in the region started as early as 2004, the use of lateral well bores did not become common until after 2007. In their study of early landcover changes, Drohan et al. (2012) chose a similar approach and did not include well-data prior to 2007. For this study, statewide data were acquired from the PA Department of Environmental Protection, the WV Department of Environmental Protection, and the OH Department of Natural Resources, respectively.

US Department of Agriculture National Agriculture Imagery Program (NAIP) imagery 1:10,000 scale was used in this study to quantify the extent of UOG development. NAIP imagery has been used to map land conversion on large geographic scales and over multiple ownership types as well as in mapping disturbance related to oil and gas development (Drohan et al. 2012; Pierre et al. 2018; Slonecker et al. 2012a, b).

Locational data from each permitted well site was incorporated into the Geographic Information System (GIS) analysis software ArcGIS ArcMap version 10.8 (Esri 2019). To determine whether construction had begun on the well sites, locational information for well permits were analyzed with respect to the most current NAIP imagery in each state at the time of this study and included 2009 and 2017 in OH, 2008, 2013, 2015, and 2017 in PA and 2007, 2009, 2011, 2014, and 2016 in WV. As the four-band color-infrared imagery was not available for the pre-development period, only three band true-color NAIP was used for the classification to maintain consistency between the datasets. The number of individual permits included 17,609 in PA, 5,294

in WV, and 2868 in OH. The permitted well locations were inspected for signs of drilling-related activity including disturbed soil, forest clearings, roadways, or previously constructed well pads. Older imagery was used to confirm the status on some sites where activity was difficult to determine. Through the comparison of multiple imagery years, the presence or absence of land use change was able to be determined for each permitted location. Wells that showed some sign of drilling activity during the study period were included and those wells that showed no signs of activity were excluded from subsequent analyses.

As multiple wells are often drilled on each well pad, wells were aggregated based on their location. After determining which wells had signs of development, a 10 m circular buffer was placed around each well on the pad. Most top-holes on a multi-well pad are within 5 m (Ogoke et al. 2014), thus closely located buffers overlapped. The 10 m buffer was chosen as it would include all wells on a pad but would not include wells from adjacent pads. The shared boundaries were dissolved for those buffers and the multiple well top-hole locations were assigned to a singular well pad. The centroid of the well pad polygon then had a 25-hectare circular buffer placed about it for use in subsequent cover-type classifications. The 25-hectare buffer selected for this study is greater than those completed in previous studies (Grushecky et al. 2022). The larger buffer size was due to the positive trend seen in total UOG related site disturbance since the 2009–2012 time-period as well as the increase found in the number of wells used per pad (Grushecky et al. 2022, U.S. Energy Information Administration US EIA (2016b)). It has been reported that the industry trend is toward a larger development area with up to 40-wells on a pad (Ogoke et al. 2014). The use of a 25-hectare buffer ensures that the complete extent of all pad and associated infrastructure is captured at the site level. This extent was verified by measuring from aerial photography and field visits to local sites.

Classifying Land Cover Associated with UOG Development

Analyzing the extent of disturbance associated with UOG development has been performed in many studies (Donnelly et al. 2017; Drohan et al. 2012; Jantz et al. 2014; Johnson et al. 2010; Liu 2021; Langlois et al. 2017; Slonecker et al. 2012a, b). The two main ways to map land cover from aerial imagery are digitizing and classification. Digitizing is done by capturing the desired features as points, lines, or polygons from the background image as a created new map layer. Some of the disadvantages of digitizing UOG development are the time-consuming nature of the process, and potential errors due to digitizer bias. In other studies that have used digitization to assess the level of disturbance,

Fig. 2 Methodological flow chart outlining the supervised classification of pre- and post-development conditions in a 25-ha buffer around a UOG unconventional well pads developed in Ohio, Pennsylvania, and West Virginia, USA
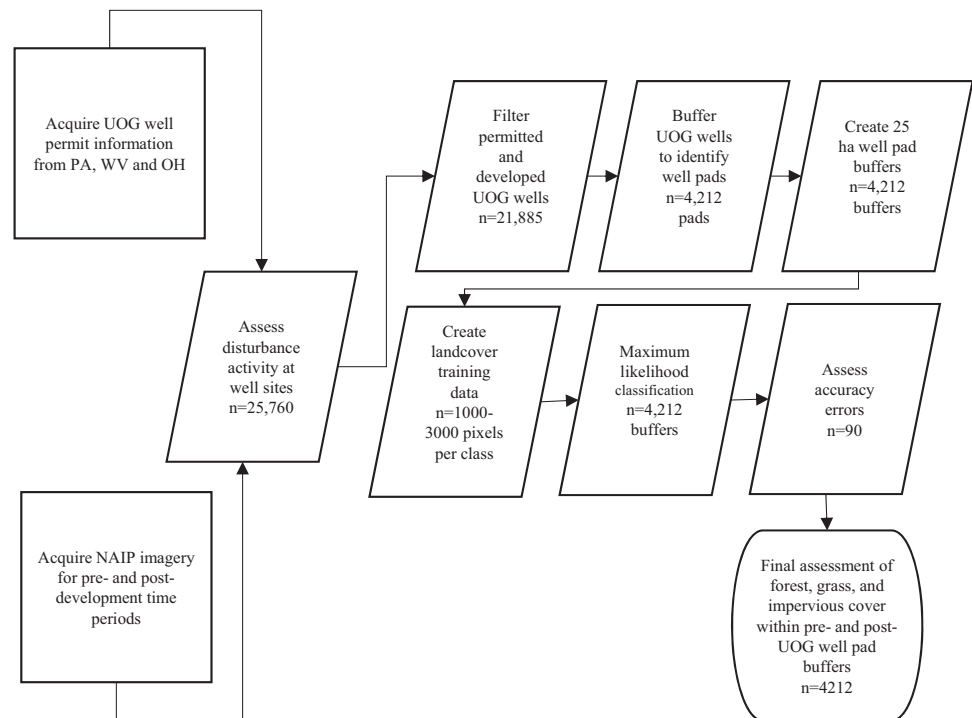
a sampling approach was used instead of a census approach (Lillesand et al. 2015).

The second common method of assessing land cover, and the approach used in this study, is to perform a classification of the imagery. In this study, we chose a supervised classification approach to assess land cover changes over time (Fig. 2). A supervised classification was chosen due to the large area extent of the classes required and the general spectral properties of the classes to be detected. The classes could also be easily edited and updated by reclassification due to misclassification with the grass and forest class. The different times of the year in which the NAIP orthophoto imagery was collected can often be a limitation; however, the phenology of the vegetation is most similar during full leaf out from late Spring to late Summer in this area of the country. Based on the orthophoto metadata of flight information of the original NAIP imagery, the majority of the imagery used was collected in the summer months June to August.

Within each well pad 25-hectare buffer, three main land cover types were assessed and included grass, forest, and impervious surfaces. These three cover types were assessed during the pre- and post-development periods (Fig. 3). These classification types were selected due to the high differentiation accuracy with which analysts can determine from aerial imagery over the large study area, as well as their prevalence across the multi-state study region. Representative samples of these cover types were collected from the entire study area, allowing different spectral properties of the same class to be captured in analysis

training data. For each class, between 1000 and 3000 pixels were used as the training data, from which spectral signatures were created. The actual number of training pixels depended on the size of the area sampled. Training data were collected at the 1:10,000 scale using the same process within every county in the study for both the pre-development and post-development imagery, which represented 2009 and 2017, 2008 and 2017, and 2007 and 2016 imagery in OH, PA, and WV, respectively. All training data were collected at a county level to improve accuracy in the classification of the pre- and post-development imagery.

The maximum likelihood classifier was used to classify the land cover using the imagery, within the 25-hectare well pad buffer. The classifier uses an algorithm to assign classification to imagery pixels based off a class mean vector and co-variance matrix calculations made from the user created training data (Lillesand et al. 2015). The classification is probability based, and each pixel in the image receives the classification of the highest probability land cover class. Due to the size of the imagery files, each county was classified individually. After the imagery was classified, the majority filter command was used in ArcMap GIS (Esri 2019) to replace neighboring cells. The majority filter tool reduced the number of isolated cells in the classification. After the majority filter produced a raster, the data were extracted for each well pad across the three states for subsequent analysis.

Classification accuracy was determined using an equalized stratified random sample approach (Ramezan et al. 2019). Within each state, thirty random points were

Fig. 3 Supervised classification of pre- and post-development conditions in a 25-ha buffer around a UOG unconventional well pad site in West Virginia, USA
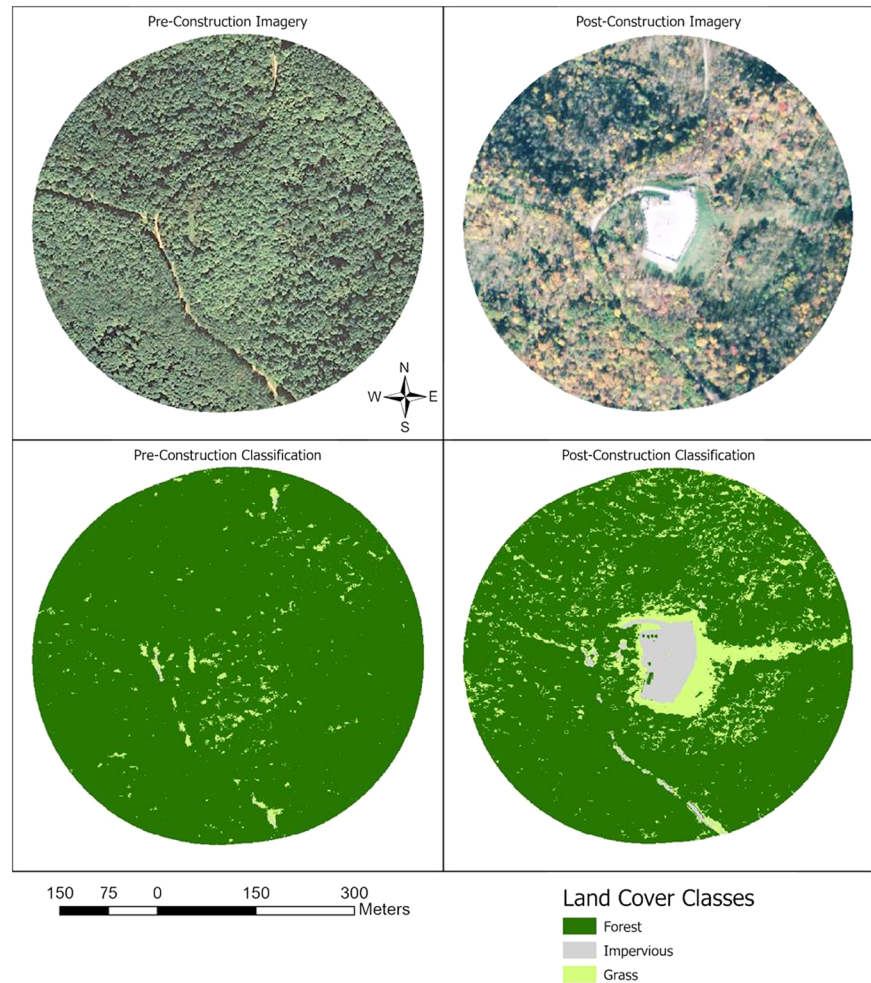
assigned to each of the three land cover classes identified in the study: forest, impervious surfaces, and grass. Each random point was used as ground reference data to compare the accuracy of the classified map with the type of land-cover that occurred at the random point. The original training data was not utilized in the accuracy assessment, as it would provide a higher biased accuracy for the classified map (Olofsson et al. 2014). A confusion matrix (Olofsson et al. 2013) was then created to ascertain the success of the image classification.

The total accuracy of the classification was calculated by adding together all cells that were identified correctly, and then dividing this sum by the total cell count of correct and misidentified cells. Although total accuracy gives the percentage of correctly identified plots, it is an average, and does not give any information on the distribution of the error between classes. Errors of omission and commission are related to the user's and producer's accuracy, which help to further analyze the accuracy of the image classification. User's accuracy describes how often the class identified will be present on the ground, while producer's

accuracy describes how often on the ground classes are identified correctly (Olofsson et al. 2013, 2014). User's accuracy is calculated by 1-commission error, while producer's accuracy is calculated by 1-omission error.

Land Cover Change Associated with UOG Development

Following the classification for the pre- and post- development periods, the area of each land cover change was calculated using the raster calculator function within Arc-GIS ArcMap (Esri 2019). The pre- and post-development rasters were summed to produce an output with nine values representing temporal changes. Each value in the output described the difference in land cover for an individual cell, such as a pre-development forest classification becoming a post-development impervious cover type. Out of the possible types of land cover change, three categories were used to monitor change in the land cover in hectares due to UOG development: (1) grass to impervious surface, (2) forest to impervious surface, and (3) forest to grass. As a pad is

developed, earth is moved, and forested areas that are located near or adjacent to the well pad and associated infrastructure either become part of unconventional development or are revegetated to grass. By omitting areas identified as impervious in 2007, development activities prior to the period of interest would not be included, as they would likely continue to be impervious in the 2016 data set.

To compare the site disturbance related UOG development across the states, generalized linear mixed models were used to investigate differences in land cover change (ha) among states and land cover type before and after unconventional development. The model was defined as:

$$Y_{ijkl} = \mu + \alpha_i + \emptyset_j + \gamma_k + \alpha\emptyset_{(ij)} + \partial_{l(i)} + \varepsilon_{(ijkl)} \tag{1}$$

where Y_{ijkl} is the change in pre/post land classification (ha), μ is the overall mean, α_i is the fixed effect of state, $\emptyset_j$ is the fixed effect of land change type (forest to impervious, forest to grass, grass to impervious), γ_k is the fixed effect of pre-forest cover (%) as a covariate, $\alpha\emptyset_{(ij)}$ is the interaction between state and land change type, $\partial_{l(i)}$ is the random effect of well pads within a state, and $\varepsilon_{(ijkl)}$ is the full model error. Pre/post land change was log transformed before all analyses. Subsequent pairwise comparisons of treatments showing significant differences were made with Tukey-Kramer adjustment for multiple comparisons. All statistical comparisons were made at the 0.05 significance level.

Site Selection Landcover Associated with UOG Well Development

For the final objective of the study, an analysis was developed to determine if there were common land cover characteristics associated with the locations of unconventional pads. To assess differences in baseline conditions, land cover was assessed in 25-hectare buffers at known well locations prior to unconventional development. Thirty random land cover samples were also developed within one county of each state where the greatest number of completed unconventional pads were observed. The thirty random 25-hectare buffers were placed in each of the selected counties, with no additional restrictions on their location. NAIP imagery was used to classify the random buffers in each of the counties. The same supervised classification methodology was used to determine the land cover distribution within the random buffers for forest, grass, and impervious cover classes. Once the imagery was clipped to the random buffers, the training data that was collected for the pre-development imagery was used as the classification dataset. The majority filter tool was then used to replace cells in the raster based on neighboring cells. The GLIMMIX procedure was used to model differences in land cover among known unconventional sites and random buffers within each of the highest well-density counties. The model

was defined as:

$$Y_{ijkl} = \mu + \alpha_i + \emptyset_j + \gamma_k + \partial_{l(i)} + \varepsilon_{(ijkl)} \tag{2}$$

where Y_{ijkl} is the percent classification of forest, grass, and impervious cover, μ is the overall mean, α_i is the fixed effect of location (either known unconventional development or random buffer), $\emptyset_j$ is the fixed effect of state, $\alpha\emptyset_{(ij)}$ is the interaction between location and state, $\partial_{l(i)}$ is the random effect of counties within a state, and $\varepsilon_{(ijkl)}$ is the full model error. Known and random location land cover classifications were log-ratio transformed due to the dependent nature of compositional categories, using the zero-replacement procedure (Aitchison 1986). Subsequent pairwise comparisons of treatments showing significant differences were made with Tukey-Kramer adjustment for multiple comparisons. All statistical comparisons were made at the 0.05 significance level.

Results

UOG Development in the Appalachian Basin

During the study period, 25,760 horizontal wells were permitted across Pennsylvania, West Virginia, and Ohio. Of the 25,760 well permits in the region, a total of 21,854 wells showed signs of surface activity as of the latest imagery available in each state. The remaining 3906 wells were permitted; however, no surface activity had commenced during the data collection period. This is a normal occurrence, as many operators permit wells that are never drilled (Litvak 2018). The 21,854 active wells were located on a total of 4212 well pad buffers (Fig. 4) across the study region for an average of 5.2 wells per pad (Table 1).

Land Cover Characteristics Associated with UOG Development

Overall accuracies on the classification of the land cover for each of the states in the study area were high. Classification accuracy was 88% for 2007 and 89% for 2017. West Virginia classification was the highest at 91% and 94% for 2007 and 2016 imagery respectively. Pennsylvania image classification produced 79% and 84% overall accuracies based on 2008 and 2017 imagery. Ohio image classification produced 92% and 88% accuracies based on 2009 and 2017 imagery.

User's accuracies ranged from 72 to 100% depending on state and time frame. User's accuracies of 100% were found in all post-development well categories, as well as in the West Virginia pre-development well category. The lowest user's accuracy was determined to be in post-development Pennsylvania imagery when classifying the forests at 72%.
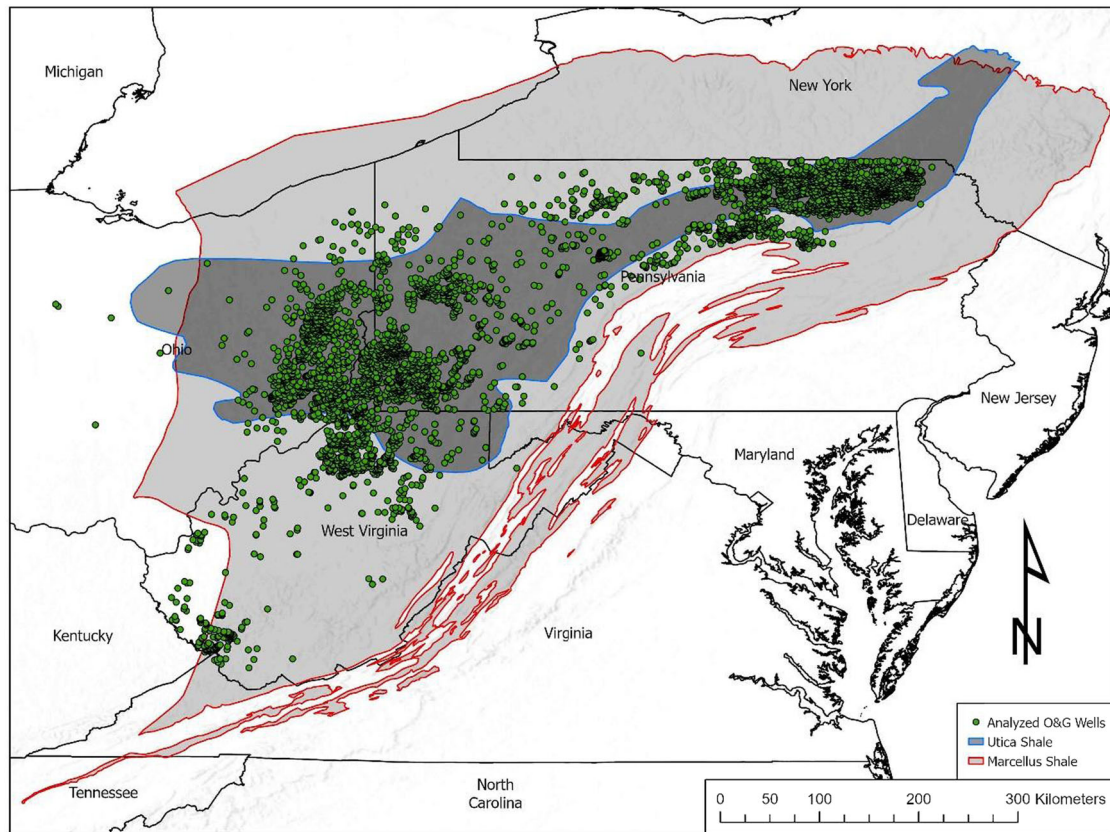
Fig. 4 Well pad locations in Pennsylvania, Ohio, and West Virginia that were assessed for land cover change due to exploration activities

Table 1 Number of permitted locations for unconventional oil and gas (UOG) wells in Pennsylvania, West Virginia, and Ohio

State	Bore hole locations permitted	Showed signs of surface disturbance	Number of well pads and pads/well
PA	17,609	15,474	2741 and 5.6
WV	5283	3731	780 and 4.8
OH	2868	2649	691 and 3.8

User's accuracies at and below 75% were also calculated in the pre-development time of Pennsylvania for the impervious and forest categories at 75% and 73% respectively.

The average percentage forest cover within the pre-development well pad buffers from the three-state study area was 66.5%. The second highest cover type was grass at 31.5%, followed by impervious surfaces at 1.9%. During the 10-year post-development period, the mean percentage of forested area within the unconventional well pad buffers was 62.2% across the region. Areas classified as grass represented 30.7% of 10-year post-development buffers, while impervious surfaces represented 7.1% of the total land cover (Table 2).

The highest average percentage forested land cover during pre- and post-development, occurred in West Virginia. The lowest average percentage of forested land cover for both time periods occurred in Ohio.

During the pre-development time periods, the average forested area inside the well pad buffers in Pennsylvania was 64.9% (Table 3), followed by a decline to 61.0% in 2017 (Table 4). Simultaneously, the percentage of impervious surface increased from 2.2% in 2007, to 7.6% in 2017. The average grass percentage in Pennsylvania decreased over the study period, from 33.0% pre-development, to 31.4% in the 10-year post-development period.

The average forested percentage for the 10-year post-development well pad buffers was 73.0% in West Virginia (Table 4), which was a large decrease from the pre-development period of 82.7%. The mean percentage of impervious surface increased during the study from an average of 1.1% in 2007 (Table 3), to 4.7% in 2017. In West Virginia, the average percentage of grass land cover during pre-development was 16.2%, which increased to an average of 22.3% during the post-development time frame.

The average forested percentage within the well pad buffers in Ohio remained consistent during the study period at 55.0% in 2007 to 54.5% in 2017. In 2007, the average percentage of impervious surface was 2.1% (Table 4). By 2017, the average percentage of impervious surface in Ohio

Table 2 Land cover proportion of the UOG well pad buffers in the Appalachian basin

Time	n	Forest Mean (%)	Forest Std. Dev	Impervious Mean (%)	Impervious Std. Dev	Grass Mean (%)	Grass Std. Dev
Pre-Development	4212	66.5	23.3	1.9	4.8	31.5	22.3
Post-Development	4212	62.2	18.4	7.1	5.7	30.7	17.6

Table 3 Pre-development land cover percentage associated with UOG development across the Appalachian basin

State	n	Forest Mean (%)	Forest Std. Dev	Impervious Mean (%)	Impervious Std. Dev	Grass Mean (%)	Grass Std. Dev
Ohio	691	55.0	24.1	2.1	4.6	43.0	23.0
Pennsylvania	2741	64.9	22.1	2.2	5.4	33.0	21.2
West Virginia	780	82.7	17.4	1.1	2.4	16.2	16.8

Table 4 Post-development land cover percentage by state across the Appalachian basin

State	n	Forest Mean (%)	Forest Std. Dev	Impervious Mean (%)	Impervious Std. Dev	Grass Mean (%)	Grass Std. Dev
Ohio	691	54.5	18.1	7.8	4.0	37.7	17.5
Pennsylvania	2741	61.0	18.0	7.6	6.3	31.4	17.6
West Virginia	780	73.0	15.2	4.7	3.7	22.3	13.6

had increased to 7.8%. The mean percentage of grass in Ohio during the pre-development period was 43.0%, which dropped to 37.7% in 2017 (Table 4).

Overall classification accuracies ranged from 80% for the pre-development Pennsylvania classification, to 94% for the post West Virginia classification. Pennsylvania post-development overall classification accuracies were the second lowest of all three states with an 84% accuracy. Compared to the other two states, Pennsylvania had the largest area classified.

All user's and producer's accuracies were above 70%, except for producer's accuracy of impervious surface for the pre-development time in West Virginia (33%). This was likely due to the limited presence of reference impervious surface sites within the pre-development imagery, with only three such points being available.

Land Cover Change Associated with well Pad Disturbance

Over the three-state study area, it was determined that a total of 23,505 hectares of land cover were impacted by UOG development. Pennsylvania contained the most land cover change in the Appalachian region, with 16,846 hectares due to UOG development. West Virginia and Ohio both had similar UOG well disturbance, with 3,423, and 3,236 hectares of land cover change, respectively.

The overall average disturbance per well pad was 5.6 ± 3.2 (mean ± standard deviation) hectares across the region. Pennsylvania had the largest disturbance per pad

with an average of 6.2 ± 3.4 hectares. West Virginia had the smallest disturbance per well pad with an average of 4.4 ± 2.5 hectares disturbed, while Ohio had an average disturbance size of 4.7 ± 2.5 hectares per well pad.

At the individual pad level, an average of 3.8 ± 2.8 hectares changed from forested land cover to a grass land cover, an average of 0.9 ± 1.1 hectares changed from grass land cover to impervious land cover, and an average of 0.9 ± 1.1 hectares of forested land cover changed to an impervious surface within the 25-hectare buffers across the Appalachian region. Overall, the amount of land area that differed among change type (forest to grass, forest to impervious, and grass to impervious) was significant (F = 1979.3, $p < 0.0001$) as was the total change in land cover type among states (F = 74.9, $p < 0.0001$). The interaction among change type and state was also significant (F = 158.4, $p < 0.0001$). According to the results from the mixed model analysis of variance, Pennsylvania had a significantly greater change in forest cover to grass (se = 0.08, t = 4.1, $p < 0.0001$) of 4.3 hectares per buffer versus a change of 3.2 hectares in West Virginia and 2.8 hectares in Ohio. Pennsylvania also had a significantly greater change in forest cover to impervious surface (se = 0.1, t = 7.7, $p < 0.0001$) of 1 hectare per buffer, in comparison to 0.7 hectares in West Virginia, and 0.6 hectares in Ohio. The grass to impervious surface change was significantly higher (se = 0.08, t = 9.9, $p < 0.0001$) in Ohio versus Pennsylvania, with a mean change of 1.3 hectares per buffer versus 0.9, and also significantly higher than the 0.5 hectares found in West Virginia (se = 0.1, t = 22.8, $p < 0.0001$). Pennsylvania also had a significantly greater
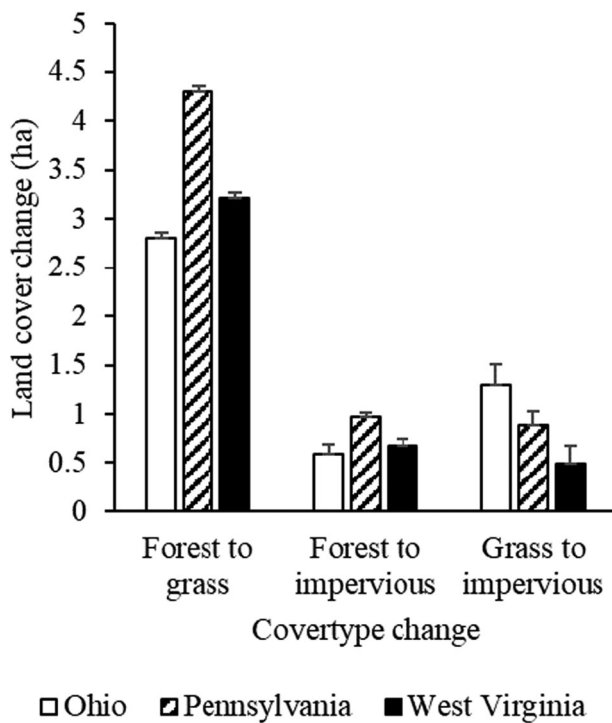
Fig. 5 The average land cover change (ha) with standard error associated with UOG development across the Appalachian basin. Land cover change quantified for forest to grassland, forest to impervious and grass to impervious cover type for the pre- to post-time periods for unconventional oil and gas development

change in grass to impervious surface (se = 0.08, t = 16.7, p < 0.0001) of 0.9 hectares per buffer versus a change of 0.5 hectares West Virginia (Fig. 5).

Landcover Associated with UOG well Site Selection

There was a significant difference (f = 5.62, p = 0.0179) in forested percent between known unconventional developed areas and the random buffers. The average percent forested in the 25-hectare active well buffers was (67.2% ± 22.7), while the average percent forest in the random buffers was 75.5% ± 24.2. No difference was found in the percent grassland area (f = 2.64, p = 0.1045) or percent impervious (f = 0.66, p = 0.4176) cover types in the unconventional developed areas versus the random buffers. Percent grassland averaged 31.1% ± 21.9 in the developed areas and 22.7% ± 22.3 in the buffer areas. Impervious surfaces averaged 1.8% in both the developed and random buffers.

Discussion

Over the 10-year period of this study, natural gas production in the Appalachian region grew from 1.2 BCF per day in January of 2007 to 26.9 BCF per day in

December of 2017 (U.S. Department of Energy USDOE (2020)). At the same time, the United States went from a net importer of 3800 BCF in 2007 to a net exporter in 2017 (U.S. Energy Information Administration US EIA (2020)). All of the production increases in the past decade across the region are linked to Pennsylvania, West Virginia, and Ohio (US EIA 2019). With greater production, associated increases in land cover change have occurred. Much of the drilling has taken place in rural areas, driving the conversion of forest and grass lands to a more industrial and impervious land use type.

Many studies have attempted to measure this change, but none have been done across the entire Appalachian basin. With over 20,000 wells and 4212 pads mapped in this project, it provides the best insight into disturbance and future patterns of development in the three-state area. This study determined that disturbance due to UOG development was higher than previously conducted studies, with an average of 5.6 hectares per well pad across the study area. However, this estimate includes all disturbance within the 25-hectare buffer which represented the well pad, access roads and additional infrastructure related to UOG development. Up to this point, the highest disturbance found due to well pad facilities was 4.2 ha in an eastern OH watershed (Liu 2021). Other research has shown that additional infrastructure beyond the well pad was found to increase disturbance between 64% (Jantz et al. 2014) and 250% (Langlois et al. 2017). By categorizing all land cover changes within the 25-ha buffers, this research was able to better characterize the disturbance of the industry due to both well pad and midstream related development.

One way to increase the overall accuracies in the study would be to use more training data. Incorporating more training data would capture broader spectral properties for each class, allowing the classification algorithm to sample more land cover. Doing so would inevitably increase the amount of processing time. Since the study extent was the Appalachian basin, the number of training samples were chosen so that the computer processing could be completed in a feasible time frame.

The majority of the research on land cover change and characteristics of UOG development in the Appalachian basin has occurred in Pennsylvania during the early stages of development with the highest pad-level disturbance reported as 2.7 hectares (Drohan and Brittingham 2012; Slonecker et al. 2012a). In Ohio, Liu (2021) found that well pads were between 3.99 and 4.18 hectare in size. Grushecky et al. (2022) found the average disturbance associated with UOG wells in West Virginia to be 4.02 hectares per well pad. In our study, we found that disturbance related to unconventional development was approximately 12%, 130%, and 12% higher than previously reported in Ohio, Pennsylvania, and West Virginia, respectively. Several

reasons can account for the greater level of disturbance found in this study. Many of the previous studies were in the early stages of development and only recorded disturbance at the well-pad and did not include additional spatially associated infrastructure. Additionally, there has been a trend in increasing the number of well bores per pad, which impacts land use and the area occupied by shale gas development (Costa et al. 2017). In earlier work, Drohan et al. (2012) concluded that over 75 percent of well pads in the state of Pennsylvania contained 1 to 2 wells. When looking at all UOG development in WV through 2020, an average of 3.8 wells were drilled per pad (Grushecky et al. 2022). That number has increased, with the average well pad in Pennsylvania currently containing 5.6 wells as determined in this study and is in-line with estimates from Liu (2021) who found at most 6 wells per pad. As companies have signed leases with landowners to secure as much of the land rights as possible, UOG development companies are now returning and drilling additional wells to previously established well pads (Litvak 2018). Based on results through 2018, West Virginia has an average of 4.8 wells per pad, and Ohio averages 3.8 wells per pad. We would expect the number of wells and the size of pads to increase in both OH and WV as development matures.

We found that the greatest UOG driven change in land cover across the Appalachian region was forested areas being converted to grass dominated lands. Forest fragmentation and the loss of core forest due to UOG development has been well documented (Drohan et al. 2012; Langlois et al. 2017; Young et al. 2018), as have the associated impacts to avian communities (Farwell et. al. 2016; Farwell et al. 2020), which of all biota may be at most risk in the region (Brittingham et al. 2014). This conversion was consistent across all three states. Because of the steep topography in the region, the cleared area for the pad is often larger because of the excess needed for cut and fill slopes. Once the pad is developed, the remaining areas surrounding the well pad are usually barren soil, which must then be seeded with grass species (West Virginia Department of Environmental Protection WVDEP (2012)). Grass land cover helps with erosion control and can also be important habitat for multiple types of wildlife (Villemey et al. 2018). Although many UOG well pads have not been fully reclaimed, most BMPs require the site be returned to original contour upon completion. The biggest limitation to revegetation success of species on disturbed areas is poor soil reclamation (Drohan and Brittingham 2012).

UOG related fragmentation commonly leads to an increase in impervious surfaces, which are a direct threat to water quality in the region. Significant trends in forest and grass land conversion to impervious surfaces were documented in this study. Unlike the other cover types, impervious surfaces add little to ecosystem services. As impervious surface increases across the landscape, so will runoff and soil erosion. This has been found to result in higher concentrations of total suspended solids (TSS) in water bodies (Entrekin et al. 2011). In Pennsylvania, Olmstead et al. (2013) found that each additional 18 well pads resulted in a five percent increase in watershed level TSS concentrations. This increase has been cited as one of the most common problems related to UOG development (Drohan and Brittingham 2012).

Pre-development site characteristics were compared to random buffers in one county from each state in the region. Although each of the selected counties represented the greatest amount of UOG development in the state, it should be noted that conditions across all counties in the region are highly variable. However, in the areas used for this study, results indicate that areas selected for UOG well sites had significantly less forest cover. This would primarily be due to the increased cost of developing a well in a forested area. The cost of developing a well pad in a forested land cover is much higher due to the labor and physical complexities of tree and stump removal. Areas that are grass land cover in the Appalachian basin are often used as agricultural fields and pastures, which are also likely less sloped. Another reason that UOG wells are located in areas with less forest cover is because of timber cutting restrictions associated with endangered species (U.S. Fish and Wildlife Service US FWS (2020)). Timber cutting restrictions are implemented in areas where there is a potential overlap with an endangered species, such as the Indiana bat (*Myotis sodalist*). Currently in West Virginia, an Indiana bat conservation plan is needed if a development involves the clearing more than 17 acres of forest (U.S. Fish and Wildlife Service US FWS (2020)). If the bats are found on the location, then the timber must be cut seasonally, which can cause significant delays and add costs to the overall development plan.

Results from this study conclude that UOG development at the well-site level has directly contributed to over 23,000 ha of surface impacts in the Marcellus and Utica shale regions of the Appalachian Basin. This represents <1% of the total area in the Marcellus and Utica shale formations. These trends are not limited to the just this region, shale development in other regions of the USA, Canada, and the UK also impact land use and surface disturbance (Costa et al. 2017). Largely, the landscape level changes identified in this study were dominated by pre-existing forested lands being converted to a grass-dominated ecosystem following the creation of well pads and surrounding infrastructure. From an ecosystem standpoint, though the modern trend of developing new UOG wells on established well pads causes the associated pad development to be larger, the overall disturbance per well is declining. However, it is expected that there will be continued UOG and renewable energy development in the

region (Evans and Kiesecker 2014), which will have continued consequences on core forest cover and associated biota. To help combat the trend of forest conversion, landscape scale disturbance patterns should be considered and incorporated into the permitting processes for energy infrastructure siting. This will, in turn, cause ongoing regional disturbances to be considered during final site selection for UOG development.

Author contributions STG, KJH, MPS, and JW contributed to original study design. Data collection and GIS analyses provided by Harris and Mesa. First draft of manuscript based on MS thesis by Harris. Manuscript developed by Grushecky and reviewed and edited by all authors.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

References

Abrahams LS, Griffin WM, Matthews HS (2015) Assessment of policies to reduce core forest fragmentation from Marcellus shale development in Pennsylvania. Ecol Indic 52:153–160. https://doi.org/10.1016/j.ecolind.2014.11.031

Aitchison, J (1986) The Statistical Analysis of Compositional Data. Chapman & Hall, New York, 416 pp

Brittingham MC, Maloney KO, Farag AM, Harper DD, Bowen ZH (2014) Ecological risks of shale oil and gas development to wildlife, aquatic resources and their habitats. Environ Sci Technol 48:11034–11047. https://doi.org/10.1021/es5020482

Costa D, Jesus J, Branco D, Danko A, Fiúza A (2017) Extensive review of shale gas environmental impacts from scientific literature (2010–2015). Environ Sci Pollut Res 24(17):14579–14594. https://doi.org/10.1007/s11356-017-8970-0

Donnelly S, Cobbinah Wilson I, Oduro Appiah J (2017) Comparing land change from shale gas infrastructure development in neighboring Utica and Marcellus regions, 2006–2015. J Land Use Sci 12:338–350. https://doi.org/10.1080/1747423X.2017.1331274

Drohan PJ, Brittingham M (2012) Topographic and Soil Constraints to Shale-Gas Development in the Northcentral Appalachians. Soil Sci Soc Am J 76:1696–1706. https://doi.org/10.2136/sssaj2012.0087

Drohan PJ, 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 Manag 49:1061–1075. https://doi.org/10.1007/s00267-012-9841-6

Entrekin S, Evans-White M, Johnson B, Hagenbuch E (2011) Rapid expansion of natural gas development poses a threat to surface waters. Front Ecol Environ 9:503–511. https://doi.org/10.1890/110053

Esri (2019) ArcGIS ArcMap Version 10.6 and Spatial Analyst Extension. Environmental Systems Research Institute, Redlands, CA

Evans JS, Kiesecker JM (2014) Shale gas, wind and water: Assessing the potential cumulative impacts of energy development on ecosystem services within the Marcellus play. PLoS ONE 9:1–9. https://doi.org/10.1371/journal.pone.0089210

Farwell LS, Wood PB, Sheehan J, George GA (2016) Shale gas development effects on the songbird community in a central Appalachian forest. Biol Conserv 201:78–91. https://doi.org/10.1016/j.biocon.2016.06.019

Farwell LS, Wood PB, Dettmers R, Brittingham MC (2020) Threshold responses of songbirds to forest loss and fragmentation across the Marcellus-Utica shale gas region of central Appalachia, USA. Landsc Ecol 35:1353–1370. https://doi.org/10.1007/s10980-020-01019-3

Grushecky ST, Zinkhan FC, Strager MP, Carr T (2022) Energy production and well site disturbance from conventional and unconventional natural gas development in West Virginia. Energ. Ecol. Environ (2022):1–11 https://doi.org/10.1007/s40974-022-00246-5

Hastings K, Heller LR, Stephenson EF (2017) Fracking and labor market conditions: A comparison of Pennsylvania and New York Border counties. East Econ J 43:649–659. https://doi.org/10.1057/eej.2015.47

Izadi G, Junca JP, Cade R, Rowan T (2014) Multidisciplinary study of hydraulic fracturing in the Marcellus shale. In 48th US Rock Mechanics/Geomechanics Symposium. OnePetro

Jantz CA, Kubach HK, Ward JR, Wiley S, Heston D (2014) Assessing land use changes due to natural gas drilling operations in the Marcellus shale in Bradford County, PA. Geogr Bull 55:18–35

Johnson N, Gagnolet R, Ralls E, Zimmerman B, Eichelberger C, Tracey G, Kreitler S, Orndorf J, Tomlinson S, Bearer S, Sargent S (2010) Pennsylvania Energy Impacts Assessment. Report 1: Marcellus Shale Natural Gas and Wind. The Nat Conserv. https://www.nature.org/media/pa/tnc_energy_analysis.pdf. Accessed 27 Oct 2021

Kargbo DM, Wilhelm RG, Campbell DJ (2010) Natural gas plays in the Marcellus shale: Challenges and potential opportunities. Environ Sci Technol 44:5679–5684. https://doi.org/10.1021/es903811p

Langlois LA, Drohan PJ, Brittingham MC (2017) Linear infrastructure drives habitat conversion and forest fragmentation associated with Marcellus shale gas development in a forested landscape. J Environ Manag 197:167–176. https://doi.org/10.1016/j.jenvman.2017.03.045

Leff, E (2015) Final Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program. Regulatory Program for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs. NY Department of Environmental Conservation. https://www.dec.ny.gov/energy/75370.html. Accessed 27 Oct 2021

Lillesand T, Kiefer R, Chipman J (2015) Remote sensing and image interpretation, 7th edn. John Wiley and Sons. New York, p 736

Litvak A (2018) These days, oil and gas companies are super-sizing their well pads. Pittsburgh Post-Gazette. https://www.post-gazette.com/business/powersource/2018/01/15/These-days-oil-and-gas-companies-are-super-sizing-their-well-pads/stories/201801140023. Accessed 27 October 2021

Liu Y (2021) Remote Sensing of Forest Structural Changes Due to the Recent Boom of Unconventional Shale Gas Extraction Activities in Appalachian Ohio. Remote Sens 13:1453. https://doi.org/10.3390/rs13081453

Ogoke V, Schauerte L, Bouchard G, Inglehart S (2014) Simultaneous operations in multi-well pad: a cost effective way of drilling multi wells pad and deliver 8 Fracs a day. Proc SPE Annu Techn Conf Exhib 3(2001):2234–2244

Olmstead SM, Muehlenbachs LA, Shih JS, Chu Z, Krupnick AJ (2013) Shale gas development impacts on surface water quality in Pennsylvania. Proc Natl Acad Sci USA 110:4962–4967. https://doi.org/10.1073/pnas.1213871110

Olofsson P, Foody GM, Herold M, Stehman SV, Woodcock CE, Wulder MA (2014) Good practices for estimating area and assessing accuracy of land change. Remote Sens Environ 148:42–57. https://doi.org/10.1016/j.rse.2014.02.015

Olofsson P, Foody GM, Stehman SV, Woodcock CE (2013) Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sens Environ 129:122–131. https://doi.org/10.1016/j.rse.2014.02.015

Pierre JP, Wolaver BD, Labay BJ, LaDuc TJ, Duran CM, Ryberg WA, Hibbitts TJ, Andrews JR (2018) Comparison of recent oil and gas, wind energy, and other anthropogenic landscape alteration factors in Texas through 2014. Environ Manag 61:805–818. https://doi.org/10.1007/s00267-018-1000-2

Popova O (2017a) Marcellus Shale Play: Geology Review. U.S. Energy Information Administration. https://www.eia.gov/maps/pdf/MarcellusPlayUpdate_Jan2017.pdf. Accessed 27 Oct 2021

Popova O (2017b) Utica Shale Play: Geology Review. U.S. Energy Information Administration. https://www.eia.gov/maps/pdf/UticaShalePlayReport_April2017.pdf. Accessed 27 Oct 2021

Ramezan CA, Warner TA, Maxwell AE (2019) Evaluation of sampling and cross-validation tuning strategies for regional-scale machine learning classification. Remote Sens 11:185. https://doi.org/10.3390/rs11020185

Ritters KH, Wickham JD, O'Neill RV, Jones KB, Smith ER, Coulston JW, Smith JH (2002) Fragmentation of continental United States forests. Ecosyst 5:815–822. https://doi.org/10.1007/s10021-002-0209-2

Sangaramoorthy T (2018) Maryland is not for Shale: Scientific and public anxieties of predicting health impacts of fracking. Extr Ind Soc 6:463–470. https://doi.org/10.1016/j.exis.2018.11.003

Scanlon B, Reedy R, Male F, Walsh M (2017) Water issues related to transitioning from conventional to unconventional oil production in the Permian Basin. Environ Sci Technol 51(18):10903–10912. https://doi.org/10.1021/acs.est.7b02185

Slonecker ET, Milheim LE (2015) Landscape disturbance from unconventional and conventional oil and gas development in the Marcellus Shale region of Pennsylvania, USA. Environ 2:200–220. https://doi.org/10.3390/environments2020200

Slonecker ET, Milheim LE, Roig-Silva CM, Fisher GB (2012a) Landscape consequences of natural gas extraction in Greene and Tioga Counties, Pennsylvania, 2004–2010. US Department of the Interior, US Geological Survey Open File Report 2012-1220, p 32. https://pubs.usgs.gov/of/2012/1220/ofr2012-1220.pdf. Accessed 27 Oct 2021

Slonecker ET, Milheim LE, Roig-Silva CM, Malizia AR, Marr DA, Fisher GB (2012b) Landscape consequences of natural gas extraction in Bradford and Washington Counties, Pennsylvania, 2004–2010. US Department of the Interior, US Geological Survey Open File Report 2012-1154, p 36. https://pubs.usgs.gov/of/2012/1154/of2012-1154.pdf. Accessed 27 Oct 2021

U.S. Department of Energy (USDOE) (2020) The Appalachian Energy and Petrochemical Renaissance. An Examination of Economic Progress and Opportunities. https://www.energy.gov/sites/prod/files/2020/06/f76/Appalachian%20Energy%20and%20Petrochemical%20Report_063020_v3.pdf. Accessed 27 Oct 2021

U.S. Energy Information Administration (US EIA) (2016a) Maps: Oil and Gas Exploration, Resources, and Production. Appalachian Basin Map Data. https://www.eia.gov/maps/maps.htm. Accessed 25 Oct 2021

U.S. Energy Information Administration (US EIA) (2016b) Trends in U.S. Oil and Natural Gas Upstream Costs. https://www.eia.gov/analysis/studies/drilling/pdf/upstream.pdf. Accessed 2 June 2022

U.S. Energy Information Administration (US EIA) (2019) Dec 2019 Monthly Energy Review. U.S. Energy Information Administration. https://doi.org/10.1044/leader.ppl.24062019.28

U.S. Energy Information Administration (US EIA) (2020) Natural gas explained. https://www.eia.gov/energyexplained/natural-gas/. Accessed 27 Oct 2021

U.S. Energy Information Administration (US EIA) (2021) Where our natural gas comes from. https://www.eia.gov/energyexplained/natural-gas/where-our-natural-gas-comes-from.php. Accessed 08 January 2022

U.S. Fish and Wildlife Service (US FWS) (2020) Range-Wide Indiana Bat Survey Guidelines. Midwest Region Endangered Species, Bloomington, MN. https://www.fws.gov/midwest/endangered/mammals/inba/inbasummersurveyguidance.html. Accessed 27 Oct 2021

Villemey A, Jeusset A, Vargac M, Bertheau Y, Coulon A, Touroult J, Vanpeene S, Castagneyrol B, Jactel H, Witte I, Denuaud N, Flamerie De Lachapelle F, Jaslier E, Roy V, Guinard E, Le Mitouard E, Rauel V, Sordello R (2018) Can linear transportation infrastructure verges constitute a habitat and/or a corridor for insects in temperate landscapes? A systematic review. Environ Evid 7:1–33

West Virginia Department of Environmental Protection (WVDEP) (2012) West Virginia Erosion and Sediment Control Field Manual, Charleston, WV. https://dep.wv.gov/oil-and-gas/Documents/Erosion%20Manual%2004.pdf. Accessed 27 Oct 2021

Young J, Maloney KO, Slonecker ET, Milheim LE, Siripoonsup D (2018) Canopy volume removal from oil and gas development activity in the upper Susquehanna River basin in Pennsylvania and New York (USA): An assessment using lidar data. J Environ Manag 222:66–75