Comparing land change from shale gas infrastructure development in neighboring Utica and Marcellus regions 2006 2015.pdf

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Comparing land change from shale gas infrastructure development in neighboring Utica and Marcellus regions, 2006–2015

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ABSTRACT

The emergent patterns of land change resulting from the development of shale oil and gas infrastructure is a result of many small decisions and interactions. This research focuses on the land change associated with the development of shale oil and gas infrastructure in the Marcellus and Utica shale formations in two geographically proximate and physically similar counties, Carroll County, OH, and Washington County, PA. Land-cover data used to measure feature-scale change were digitized from aerial photography and then used to update National Land Cover Dataset data used in the calculation of forest fragmentation for the entire study areas. The amount and pattern of land change was very similar between the two counties even though they are drawing oil and gas from different shale formations. Less than 1% of the total forest for each county was lost but the fragmentation impacts are amplified by the pattern of infrastructure on the landscape.

Introduction

The extraction of natural gas and oil from shale increased dramatically in the United States in the last two decades due to the confluence of drilling technologies and higher energy prices. Regions that had not had lucrative extractive industries in decades, such as areas in the Marcellus and Utica shale formations in eastern United States, boomed with drilling-related activity. Among other ecosystem impacts, land change from the construction of shale gas well pads and associated infrastructure may cause disturbances such as deforestation (Brittingham, Drohan, & Bishop, 2013), water quality (Olmstead, Muehlenbachs, Shih, Chu, & Krupnick, 2013; Warner, Christie, Jackson, & Vengosh, 2013), loss of habitat (Brittingham, Maloney, Farag, Harper, & Bowen, 2014) and biodiversity (Kiviat, 2013), air quality degradation (Annevelink, Meesters, & Hendriks, 2016), noise pollution, and safety issues from vehicular traffic and drilling operations (Graham et al., 2015). Efforts to monitor and quantify the amount of land change caused by shale oil and gas development have been challenging because of the rapid overall pace and uneven geographic development. For example, numerous well pads may be built in an area but not connected via pipelines until several years later. Due to much lower oil and gas prices on the global market, the shale gas boom has dramatically slowed in most areas of the United States since 2015 (United States Energy Information Administration [USEIA], 2016a). This slowdown provides stakeholders and scientists a chance to assess the short-term impacts and model long-term impacts to better prepare for the likely return of higher oil and gas prices and the concomitant return of shale gas-drilling activities.
Existing research on land-change impacts from shale gas drilling in the Eastern United States has focused on development in the Marcellus Shale, especially in Pennsylvania, because of earlier and more intense development in this region. Neighboring areas, such as development in the larger and deeper Utica Shale, have gone largely unstudied because the development began later and have been less intense than in the Marcellus. Land change has been quantified using land cover data derived from aerial photos and satellite imagery (Drohan, Brittingham, Bishop, & Yoder, 2012; Slonecker & Milheim, 2015; Slonecker et al., 2012). These studies assessed shale gas-related land change up to 2010 and found that shale gas development has caused a substantial increase in forest fragmentation (Drohan & Brittingham, 2012; Drohan et al., 2012; Slonecker & Milheim, 2015; Slonecker et al., 2012). While conclusions about land change are similar in these studies, directly comparing the results is more challenging because of methodological differences in how land change was measured. These differences are driven by the trade-off between higher accuracy for a smaller study areas or lower accuracy for larger study areas. Some studies created high spatial resolution data through labor-intensive manual tracing of the boundaries of change features (Slonecker et al., 2012) while others have opted for buffering well locations and center lines (Drohan et al., 2012) and extant land cover datasets (Drohan et al., 2012; Slonecker & Milheim, 2015). Because of the width and linear nature of important land-change features, such as pipeline right of way (ROW) and access roads, commonly used land cover datasets may overestimate land-change area and underestimate landscape fragmentation.

While the proximate causes of land change resulting from shale oil and gas development are becoming clear, the amount and pattern of land change in a given location is influenced by several local conditions. Among these influences are existing land cover, the type and market value of extracted petroleum products, changing drilling technologies and methods, patterns of land ownership, land owner associations, and topography and soil conditions. Gathering pipelines, moving gas from well head to processing facility, cause a substantial amount of land change (Slonecker et al., 2012) but are largely unregulated in these areas. Regulations about gathering pipelines are not identical from state to state, but unless a pipeline crosses a protected area, such as wetlands (Schmid & Company, 2012), or an accident that causes injury occurs, the pipelines are not monitored in any systematic way. In the Marcellus and Utica regions, much of the land developed for shale oil and gas extraction is in the hands of private, relatively small land holders (Brittingham et al., 2013; Drohan et al., 2012), such that aggregate land change is a function of many smaller negotiations, interactions, and decisions. Adding further complexity to ownership questions is the fact that subsurface mineral rights are separable from surface rights and ‘forced pooling’ laws may require landowners to participate in leases even if they prefer not to. The combination of increasingly long horizontal wells, the pattern of small, private landholdings, and land-leasing dynamics has created new types and scales of interactions for those landowners who are willingly or unwillingly involved in the development of shale oil and gas. These interactions include formalized institutions, such as landowner associations that may include tens or hundreds of members, and more informal interactions, such as conflict between neighbors that disagree about shale gas development.

Strategies for predicting the land-change impact of shale oil and gas infrastructure hold the potential to reduce negative ecological impacts in future development. Racicot et al. (2014) predicted the potential increase in forest fragmentation from shale gas infrastructure by measuring changes seen in the US state of Pennsylvania and applying them to a forested area of the Canadian province of Quebec that has a high gas potential. Johnson et al. (2010) tested several scenarios of different development intensities and their impact on forest fragmentation and other ecosystem services in Pennsylvania. These modeling efforts are valuable in helping assess the trade-offs (Milt, Gagnolet, & Armsworth, 2016) from new methods for decreasing impacts from future developments such as colocating access roads and pipelines (Abrahams, Griffin, & Matthews, 2015) and consolidating new wells onto existing well pads (Klaiber, Gopalakrishnan, & Hasan, 2016).
To understand and model how these local interactions translate into land-change outcomes, the land change itself must be measured and compared at different locations. This research focuses on the land change associated with the development of shale oil and gas infrastructure in two geographically proximate and physically similar counties, Carroll County, Ohio, and Washington County, Pennsylvania. The shale oil and gas resources in these two counties come from different shale formations, were developed at different times by different companies, and are subject to different state and local regulations. In this paper, we first measure the amount and pattern of land change that directly results from the development of shale gas and oil infrastructure in each county. Next, we describe the land-change characteristics associated with each type of shale oil and gas feature and the forest fragmentation that results from shale oil and gas infrastructure in these landscapes. And finally, we assess any differences in patterns of land change and forest fragmentation given the different development histories in these two counties.

Study area
Carroll County, Ohio, and Washington County, Pennsylvania, are of particular interest for comparison because they are geographically proximate, separated by approximately 30 km at the closest point, but have important differences in their histories of shale oil and gas development (Figure 1). Falling in the Western Allegheny Plateau Level III ecoregion (United States Environmental Protection Agency Office of Research and Development [US EPA ORD], 2013), both counties have similar topography and native vegetation dominated by mixed oak forests and mixed mesophytic forests. Both counties are about 55% forested with the remaining land predominantly in agricultural uses (Table 1). The forest and agricultural lands are generally mixed and evenly distributed throughout each county. The percentage of Washington County that is in developed land use is about twice as much as Carroll County. Urban land uses tend to be clustered near the center of each county (see Figure 4).

Figure 1. Location of Carroll County and Washington County with all well heads of horizontal gas wells in Ohio (OH) and Pennsylvania (PA). Shale well locations in West Virginia (WV) not included.
In 2015, Washington County had a population of 208,261 with a land area of approximately 2230 km$^2$ (United States Census Bureau [USCB], 2015). Washington County has approximately twice the land area of Carroll County and a much higher population density, especially in the northeast portion of the county, due to its proximity to the large urban center of Pittsburgh, PA (Figure 1). Washington County had the first unconventional shale oil and gas wells in the state of Pennsylvania drilled into the Marcellus Shale in 2003 (Brasier et al., 2011) but widespread drilling activity did not begin until several years later (PennFuture, 2014).

Carroll County, Ohio, is a rural county with a population of 27,811 in 2015 (USCB, 2015) and a land area of approximately 1033 km$^2$. The largest town and county seat, Carrollton, had a population of approximately 3200 people in 2013. The first unconventional shale oil and gas wells were developed in 2011 and while other counties in Ohio had been drilled prior to this, Carroll County has seen by far the most shale oil and gas development in the state (Auch, 2015). The shale wells in Carroll County are drilled into the Utica Shale formation.

Important for the spatial pattern of land change, the depths of the Utica and Marcellus shale in the two counties are similar at approximately 5000–8000 ft (United States Energy Information Administration [USEIA], 2016b, 2016c). In general, the price of natural gas, as well as petroleum products, peaked in 2008 and spurred the development of shale gas extraction (Figure 2). The natural gas from the Utica Shale contain more ‘wet’ gasses, such as ethane and propane, while the Marcellus produces primarily ‘dry’ methane. This difference has influenced when and how many wells have been developed in the two counties (Figure 2). The massive increase in production of methane decreased its value and increased the relative value of wet gasses making drilling in the Utica more attractive.

| Table 1. Area of land-cover classes prior to shale oil and gas development. |
|-----------------|--------|--------|--------|--------|--------|
|                 | Developed | Forest | Agriculture | Water | Total  |
| Carroll County  | 72.18 (6.99%) | 573.23 (55.54%) | 372.55 (36.10%) | 14.15 (1.37%)| 1032.12 |
| Washington County| 321.71 (14.43%) | 1230.95 (55.21%) | 645.57 (28.95%) | 13.52 (0.61%) | 2229.75 |

Land-cover values for Carroll County derived from 2011 NLCD (Homer et al., 2015) and values for Washington County derived from 2006 NLCD (Fry et al., 2011). All areas reported in km$^2$ with percent of total area in parentheses.

Figure 2. Number of shale gas wells permitted for Carroll County, OH (ODNR, 2016), and Washington County, PA (PADEP, 2016), with US Natural Gas Industrial Price (USEIA, 2016d) from 2005 to 2015.
Utica wells in Carroll County have also produced much more oil, by nearly a 10-fold margin at their respective peak outputs, than the Marcellus wells in Washington County (DrillingEdge, 2016).

Data and methods

Feature-scale land change

Land-cover data used to measure feature-scale change were digitized from aerial photography. Land change occurred continuously over the study period, so several sources of imagery were utilized. Imagery was obtained for Carroll County from the Ohio Statewide Imagery Program (OSIP, 2011) for the years 2006 and 2010. Imagery for Washington County was obtained from Pennsylvania Spatial Data Access (PASDA, 2016) for the years 2005 and 2010. Imagery from the National Agriculture Imagery Program (NAIP, 2016) covered both counties and was obtained for the years 2013 and 2015. All aerial photography was natural color and orthorectified with a spatial resolution of no greater than 2 m. The most recent time point of imagery prior to construction for each well was used to determine the land-cover type before development. Although drilling, and even hydraulic fracturing, has occurred for much longer, this research only includes land change that occurred from 2006 to 2015 when the combined use of horizontal drilling and hydrologic fracturing changed the viability of recovery and thereby the pattern of land change.

Land-cover classes were determined from examining the aerial imagery to best address the basic question of what land-change features are produced during shale gas development. Instead of working in chronological order and first digitizing the entire landscape prior to shale gas development, polygons were created representing areas where shale gas-related land change occurred. These polygons were then overlaid on aerial photos acquired prior to development and the predevelopment land-cover class was assigned to these land-change features. Prior to development, land was categorized as hay/crop, forest, pasture, or residential. After development, land was categorized as pipeline ROW, well pad, disturbance, road/pavement, retention pond, or other infrastructure (Figure 3). The ‘disturbance’ category contains areas that were cleared during construction around the perimeter of other features such as well pads. These areas generally were replanted to grass or left bare during the study period. In Carroll and Washington Counties, ‘other infrastructure’ is primarily composed of compressor stations that are buildings that house pumps used to increase the pressure in the gathering pipelines.

When land change from one feature type to another did occur, such as disturbed area changing to pipeline ROW, the area was assigned to the later feature type. The interpretation and digitizing process produced a vector polygon dataset where each polygon has a land-cover class prior to development and the post-development land-cover class was assigned to these land-change features. Prior to development, land was categorized as hay/crop, forest, pasture, or residential. After development, land was categorized as pipeline ROW, well pad, disturbance, road/pavement, retention pond, or other infrastructure (Figure 3). The ‘disturbance’ category contains areas that were cleared during construction around the perimeter of other features such as well pads. These areas generally were replanted to grass or left bare during the study period. In Carroll and Washington Counties, ‘other infrastructure’ is primarily composed of compressor stations that are buildings that house pumps used to increase the pressure in the gathering pipelines.

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Landscape-scale fragmentation

A comprehensive land-cover dataset was required to assess land change and forest fragmentation at the landscape scale. The National Land Cover Dataset (NLCD) is produced for the entire United States from Landsat data approximately every 5 years. The spatial and temporal resolution of the
NLCD make it insufficient to map the feature-level land change using only this dataset, but it does provide an efficient way to describe predevelopment land cover for the entire study area (Figure 4). For use in the fragmentation analysis, the NLCD datasets were reclassified such that all pixels in any forest categories were placed in one category and all other pixels were classified as non-forest. Because development of the shale oil and gas infrastructure began at different times in the two study areas, the 2006 NLCD (Fry et al., 2011) was used to represent predevelopment Washington County and the 2011 NLCD (Homer et al., 2015) was used to represent predevelopment Carroll County.
County. To measure landscape-scale fragmentation, the digitized land-cover change polygons described above were applied to the NLCD by assigning the pixels in the NLCD to the non-forest category.

The 30-m pixel size of the NLCD is too large to capture features such as the pipeline ROW. At approximately 20 m in width, pipeline ROWs would either be too small to be represented by a pixel or would be overrepresented by a pixel. This mismatch would strongly affect spatial patterns observable in the data. The potential undesirable effects of this issue are increased by the fact that the likelihood of the majority of a pixel being occupied by a digitized feature is dependent upon the orientation of the digitized feature to the columns and rows of the NLCD raster dataset. For example, the spatial representation of a pipeline ROW oriented due east–west will remain more intact than a ROW-oriented northeast–southwest. To mitigate this issue, the NLCD datasets were resampled from a spatial resolution of 30–10 m before the land-change polygons were applied. The origin location of the resampled grid was forced to coincide with that of the original grid.

FRAGSTATS version 4.2 (McGarigal, Cushman, & Ene, 2012) was used to calculate landscape metrics on the forest land-cover datasets. The need for a minimum, adequate set of landscape metrics is a continuing challenge (Cushman, McGarigal, & Neel, 2008) so a small number of metrics were selected to compare both composition and configuration before and after land change from shale oil and gas development (Table 2). Metrics were calculated for the NLCD data for each county, representing the landscape prior to the development of shale oil and gas infrastructure, and the NLCD data for each county with the digitized land-cover change features imposed, representing the landscape post-development. The eight-neighbor rule of adjacency and a 40-m edge distance (Harper et al., 2005) were used in FRAGSTATS.

Rather than calculating metrics for the forest of the entire county, the intersection of the county boundary and the convex hull of the land-change features (dashed line in Figure 5) was used to limit the extent of the dataset used in FRAGSTATS. The reasoning for this choice was that development of shale oil and gas infrastructure has not extended across all of either county and so comparing the affected areas would be more appropriate. The convex hulls of the land-change features contained 80.7% of Carroll County and 88.4% of Washington County, respectively.

**Results**

The total area of land change directly resulting from shale oil and gas development in Washington County was approximately double the change in Carroll County (Tables 3 and 4). Washington County is 2.16 times larger than Carroll County in total land area and so the density of land change is very similar in the two study areas. Pipeline ROWs are the infrastructure feature type that results in the most land change accounting for more than half of the total in each of these two counties.

| Table 2. FRAGSTATS metrics used to quantify landscape fragmentation. |
|------------------------|------------------------------------------------------------------|
| Metric                 | Description                                                      |
| PLAND                  | Percentage of the landscape comprised by all forest patches       |
| NP                     | Total number of forest patches                                    |
| LPI                    | The percentage of the landscape comprised by the largest forest patch |
| MNAREA                 | Mean area of forest patches                                       |
| AREA CV                | Coefficient of variation of forest patch area                     |
| MNSHAPE                | Mean shape index value for all forest patches where values increasing from 1 (square patch) indicate more complex forest patch shapes |
| SHAPE CV               | Coefficient of variation of forest patch shape                    |
| AI                     | Aggregation index expressed as a percentage where a value of 0 corresponds to no adjacent forest cells and a value of 100 corresponds to a single, compact patch |
| CORE                   | Total core area where core is defined as the interior portion of the patch that is greater than the specified depth-of-edge distance |
The ratio of land change resulting from pipeline ROWs to the total area of the counties, 2.30, was also very similar to the ratio of the total area of the counties.

In further comparing the land change between counties, many of the land-change totals exhibit consistent patterns with a few important exceptions. In Carroll County, change from hay/crops was the most common conversion, while in Washington County, conversion from forest category was most common. This is of note given that percent of the counties in forest is very similar (Table 3). Additionally, the rank of each land-cover type in which shale oil and gas features were created was consistent across feature types except for well pads. Well pads were less likely to be created in forested areas in Carroll County than in Washington County.

The density of well pads (well pads/area) was very similar in the two counties but the well pads in Carroll County were nearly 20% larger on average. The amount of land changed due to the construction of access roads and retention basins (ponds) is lower per well pad in Carroll County. So, while the overall ratio of land change to land area is very similar in the two counties, there is variation in the amount of each category of land cover that was changed and the amount of area

### Table 3. Land change results for Carroll County, OH, interpreted from aerial photos.

<table>
<thead>
<tr>
<th></th>
<th>After</th>
<th>Before</th>
<th>Pipeline ROW</th>
<th>Disturbance</th>
<th>Well pad</th>
<th>Road</th>
<th>Pavement</th>
<th>Pond</th>
<th>Other infrastructure</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hay/Crops</td>
<td>364.18</td>
<td>158.35</td>
<td>76.83</td>
<td>29.19</td>
<td>27.42</td>
<td>12.20</td>
<td>6.61</td>
<td>674.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>303.75</td>
<td>77.98</td>
<td>33.33</td>
<td>14.36</td>
<td>2.46</td>
<td>1.86</td>
<td>3.54</td>
<td>437.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture</td>
<td>35.89</td>
<td>95.18</td>
<td>43.33</td>
<td>16.89</td>
<td>15.90</td>
<td>6.39</td>
<td>1.04</td>
<td>215.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>8.32</td>
<td>2.05</td>
<td>0.09</td>
<td>0.89</td>
<td>0.41</td>
<td>0.00</td>
<td>0.91</td>
<td>12.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>712.14</td>
<td>333.74</td>
<td>153.58</td>
<td>61.33</td>
<td>46.19</td>
<td>20.45</td>
<td>12.1</td>
<td>1339.53</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Units are ha.

### Table 4. Land change results for Washington County, PA, interpreted from aerial photos.

<table>
<thead>
<tr>
<th></th>
<th>After</th>
<th>Before</th>
<th>Pipeline ROW</th>
<th>Disturbance</th>
<th>Well pad</th>
<th>Road</th>
<th>Pavement</th>
<th>Pond</th>
<th>Other infrastructure</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hay/Crops</td>
<td>550.44</td>
<td>266.87</td>
<td>91.75</td>
<td>57.68</td>
<td>19.22</td>
<td>38.53</td>
<td>15.09</td>
<td>1039.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>807.79</td>
<td>341.77</td>
<td>76.71</td>
<td>61.03</td>
<td>7.29</td>
<td>9.83</td>
<td>65.68</td>
<td>1370.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture</td>
<td>264.39</td>
<td>155.96</td>
<td>52.76</td>
<td>41.72</td>
<td>28.05</td>
<td>18.15</td>
<td>14.59</td>
<td>575.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>20.82</td>
<td>0.92</td>
<td>0.53</td>
<td>1.15</td>
<td>0.00</td>
<td>0.00</td>
<td>4.15</td>
<td>27.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1643.44</td>
<td>765.52</td>
<td>221.75</td>
<td>160.58</td>
<td>54.56</td>
<td>66.51</td>
<td>99.51</td>
<td>3012.87</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Units are ha.
converted to each type of shale oil and gas feature that may point to differences in local decision-making.

The overall pattern of land change resulting from the development of shale gas infrastructure is similar in the two counties (Figure 5). There are a number of well pads in each county that have not been connected to the network of pipelines but the spatial pattern of these disconnected well pads is different in the two counties. In Carroll County, disconnected well pads are generally to the east and quite distant from the existing pipeline network. In Washington County, the disconnected well pads are much closer to the existing network. While both counties have large areas with very little shale gas-related land change, the land cover in these unchanged areas is different. The unaffected area in Carroll County is to the east and is dominated by forest and agricultural land cover, whereas the unaffected area in Washington County comprises much more urban development.

The fragmentation of forest due to shale oil and gas infrastructure is similar in the two counties with identical direction of change in all calculated landscape metrics (Table 5). The percentage of the landscape in forest and the mean forest patch area is nearly identical in the two counties prior to land change. In each county, there was only about a 1% decrease in percentage of the landscape in forest, but this change resulted in a substantial increase in the number of forest patches. These smaller forest patches have less complex shapes and less core area. The magnitude of change was greater in each of these metrics in Washington County as compared to Carroll County but not by large margins.

### Table 5. Forest fragmentation in Carroll County, OH, and Washington County, PA.

<table>
<thead>
<tr>
<th>Landscape metrics for forest class</th>
<th>Carroll County</th>
<th>Washington County</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2011 2015 Change (%)</td>
<td>2006 2015 Change (%)</td>
</tr>
<tr>
<td>PLAND</td>
<td>54.39% 53.83% −1.03</td>
<td>55.26% 54.46% −1.47</td>
</tr>
<tr>
<td>NP</td>
<td>936 1307 39.64</td>
<td>2410 3545 47.10</td>
</tr>
<tr>
<td>LPI</td>
<td>8.02 6.09 −24.06</td>
<td>5.82 3.74 −35.74</td>
</tr>
<tr>
<td>MNAREA (ha)</td>
<td>48.42 34.32 −29.12</td>
<td>45.17 30.27 −32.99</td>
</tr>
<tr>
<td>AREACV</td>
<td>753.14 741.27 −1.58</td>
<td>902.69 846.23 −6.25</td>
</tr>
<tr>
<td>MNSHAPE</td>
<td>1.99 1.87 −6.03</td>
<td>1.82 1.53 −15.93</td>
</tr>
<tr>
<td>SHAPECV</td>
<td>90.48 81.86 −9.53</td>
<td>88.20 79.63 −9.72</td>
</tr>
<tr>
<td>CORE (ha)</td>
<td>25,281 24,327 −3.77</td>
<td>59,126 56,032 −5.23</td>
</tr>
</tbody>
</table>

All changes are calculated as percent change from initial values.

Discussion

Perhaps, most striking about the amount and pattern of land change associated with shale oil and gas development in the Marcellus and Utica study areas is the similarity. The two counties are geographically proximate and share similar physical surface and population characteristics, but, as described above, the timing of the drilling in the two counties, the companies undertaking the drilling, the shale formations and products being extracted, and the county and state regulations are different. These similarities suggest that even though there are underlying differences in production details, the landscape-scale land-change impacts of shale oil and gas infrastructure might be generalizable to locations with similar physical characteristics. More studies are needed to better understand what land-change characteristics are common across study areas and which are impacted by local physical conditions or construction methods. Market prices make the ‘when’ of shale oil and gas drilling difficult to predict, but predictability in landscape-scale land-change impacts can help communities make better informed decisions if and when the opportunity arises.

Also, clear from the feature-level results is that the construction of pipeline ROWs is far and away the largest cause of land change associated with shale oil and gas production. The land change from pipeline ROWs is also likely underestimated because of insufficient temporal resolution in the remote-sensing time series. These pipeline ROWs are almost entirely for gathering
pipelines that run from the well pads to the compressor stations. This distinction is important for several reasons. First, gathering pipelines are locally, if at all, regulated. In Ohio, there is very little oversight of gathering pipelines and authorities are only involved or even aware of the location of pipelines when problems arise such as accidents that require emergency services or sensitive land cover, such as wetlands, are involved. The regulations are slightly more stringent in Pennsylvania. Second, pipelines traverse much more distance and thereby potentially involve many more individual landowners in their construction than do the other infrastructure features. The lease of pipeline ROWs is primarily done with individual landowners rather than groups of landowners as is the case with the lease of surface and mineral rights that are involved in drilling wells. Finally, because pipelines will always be necessary to connect wells to processing facilities, increases in the average distance between wells from increased horizontal well length will not result in an equivalent reduction in land change.

As seen in the map of land-change features (Figure 5), the well pads that are not yet connected to the pipeline network are distributed differently in the two counties. Because Carroll County sits on the eastern edge of the Utica shale play, it is a reasonable that those disconnected well pads represent well that were drilled but did not show enough production to warrant the cost of connecting them to the distant pipeline network. The disconnected well pads in Washington are much closer to the existing pipeline network and would therefore have a higher likelihood of being connected in the future. Whatever the underlying reason, connecting the disconnected well pads to the existing pipeline network would result in different amounts of land change in the two counties because of their proximity to previous development.

The amount of forest loss is less than 1% of the total forest for each county but the fragmentation impacts are amplified by the pattern of infrastructure on the landscape. These results agree with other studies undertaken in this region (such as Slonecker et al., 2012; Slonecker & Milheim, 2015), but the actual amounts of change are difficult to compare because of differences in study period and details of measurement method. The factors that influence well pad placement, such as increasingly long horizontal wells, increase the dispersion of disturbance across the landscape. The amount of fragmentation, mostly caused by the network of pipeline ROWs connecting wells and processing facilities, is certainly a function of the specific pattern of forest in the landscape but both of these counties have very typical forest patterns for unglaciated landscapes dominated by small farms.

Resampling the NLCD data from 30 to 10 m cell size to more accurately represent the digitized land-change features could impact the reported shape metrics by increasing the potential edge length of a patch. With smaller cells, a more complex edge with little change in patch area would lead to a more complex shape metric. Because the same procedure was followed in both study areas in this research, the results for the two counties in this study are comparable. As with any differences in resolution when calculating landscape metrics, care should be taken in comparing these values to other metrics derived from NLCD products.

The importance of the amount and pattern of different feature types also comes from how the land involved in those features will potentially change in the future. For example, the two categories that account for the largest amount of change in both counties are pipeline ROWs and the disturbance surrounding well pads. In terms of land cover, these two land changes are initially very similar with clearing of the land followed by planting of grass or other vegetation. Over time, however, the land-change trajectories of these two features may diverge as the easements on the pipeline ROWs restrict many land uses and land covers. Of particular note in this research, no trees are allowed to grow on the pipeline ROWs, so areas that were deforested will not return to forest in the near future and the resulting fragmentation will be persistent. The duration of this mandatory suppression of forest succession is unknown but will likely persist for decades. Disturbed areas around well pads, however, may be allowed to regrow vegetation but such regrowth will have less mitigating impact on fragmentation because of the spatial pattern of this type of feature. Both the total and proportional amounts of forest that were removed and the
The total and proportional amounts of pipeline ROW that were created were higher in Washington County thereby increasing this path-dependent effect.

The findings in this paper about the patterns of change help to identify meaningful questions about the underlying processes. For instance, while the aggregate patterns of land change in the two study areas are similar, the fact that well pads in Carroll County are on average larger in area, less likely to be built in forest areas, and have less land change due to access roads than well pads in Washington County suggests that different siting considerations may be influencing the decision processes. As suggested by several authors (e.g. Abrahams et al., 2015; Klaiber et al., 2016), colocating access roads and pipelines could significantly reduce the forest-fragmentation impacts of shale oil and gas development. Likewise, better understanding the household-scale dynamics at play in siting pipelines will lead to better prediction, and potentially reduction, of the complexity of the path of pipeline ROWs. Land-change measurements, such as the average amount of gathering pipeline or other disturbance per well pad, can be used to both train and test future models of this process with the goal of communicating aggregate outcomes of many individual decisions to stakeholders. The role of both physical characteristics, such as the existing land ownership patterns, and social components, such as existing social networks, of the system need to be better understood to develop strategies that mitigate impacts from future shale oil and gas development.

**Conclusions**

The goal of this research was to compare the amount and pattern of land change in two nearby counties at a point in time when active infrastructure development was minimal. The amount and pattern of land change was very similar between the two counties even though they are drawing oil and gas from different shale formations. These findings contribute to two important efforts relating to future shale oil and gas development. First, this study examines an area in the Utica shale formation that had not previously been studied and increases the generalizability of models to better predict the impacts of shale gas development. New shale oil and gas well development decreased to almost zero in 2015, but interest in the area is again growing with increased oil prices, construction of processing facilities (Bradwell, 2016), newly available mineral rights leases on public lands (Lavalley, 2016), and connection to interstate pipelines (Sandy, 2016). Second, these findings can contribute to the research attempting to identify ways in which the negative impacts can be avoided by policy efforts to influence the spatial arrangement of disturbances. Finally, efforts to estimate the economic costs of decreasing ecological impact in energy production require robust and repeatable methodologies to measure the impacts.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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