Forest cover changes due to hydrocarbon extraction disturbance in central Pennsylvania (2004–2010)

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1. Introduction

According to the 2001 National Land Cover Dataset (NLCD) (Homer et al., 2015), about 60% of Pennsylvania is covered by forest, concentrated mostly in the central and north-central parts of the state. This forested land is also the main area of focus for hydraulic fracturing of the Marcellus shale (Figure 1; Slonecker, Milheim, Roig-Silva, & Fisher, 2012). The rapid expansion and development of oil and gas extraction in Pennsylvania has gained much attention, not only because of the increase in production due to advancements in technology, but also because of environmental concerns about some of these technologies (e.g. hydraulic fracturing). Several studies have documented the negative impacts that oil and gas development can have on the environment (Barbot, Vidic, Gregory, & Vidic, 2013; Entrekin, Evans-White, Johnson, & Hagenbuch, 2011; Gregory, Vidic, & Dzombak, 2011; Johnson et al., 2010; Kargbo, Wilhelm, & Compbell, 2010; Marcellus Shale Advisory Commission, 2011; Nicot & Scanlon, 2012; US EPA, 2011; Vidic, Brantley, Vandenbossche, Yoxthereim, & Abad, 2013). For instance, Johnson et al. (2010) estimates that about 12 ha of forest are affected for every Marcellus Shale extraction site, including well pads, roads, pipes and a buffer zone. He also estimates that the number of wells in Pennsylvania will continue to increase in the current focal areas located in the southwest and northeast regions of the state.

These recent studies concentrate on unconventional oil and gas (UOG) activities; however, without considering conventional development sites, it is challenging to assess the cumulative disturbance from oil and gas development in the state (Slonecker, Milheim, Roig-Silva, & Fisher, 2012). Distinguishing conventional oil and gas (COG) from UOG activities is challenging but not necessarily impossible. Conventional sites are those that use traditional methods for oil and gas extraction. For example, crude oil and natural gas that is produced by a well drilled into a geologic formation in which the reservoir and fluid characteristics permit the oil and natural gas to readily flow to the wellbore. Unconventional sites are those that use other modern approaches for oil and gas extraction (e.g. hydraulic fracturing) (See the U.S. Energy Information Administration Glossary, 2015).

Here, we present an assessment of the impact of such activities in the forests of 35 counties and their intersecting sub-watersheds in Pennsylvania during the years 2004–2010. The assessment ranks counties and sub-watersheds based on the cumulative impacts of oil and gas activities (both conventional and unconventional) Main Map. A series of landscape metrics were calculated before and after the oil and gas activities (2004–2010) and each subsequently ranked. The final score, computed from the ranks, represents the amount of change: lower scores represent larger changes in the forest metrics, while higher scores represent smaller changes in the forest metrics. Overall 35 counties were examined, containing 929 sub-watersheds.

2. Methods

The collection of land cover change data was a manual process whereby high-resolution 1 m imagery from...
the National Agricultural Imagery Program (NAIP) (U.S. Department of Agriculture, Farm Service Agency, 2011) was visually examined for each county over four dates to identify and digitize a disturbance footprint resulting from the development of oil and gas extraction infrastructure. Data collection was concentrated on features attributable to the construction, use and maintenance of gas extraction and drill sites, processing plants and compressor stations. Data were also collected on the center lines for new roads related to such sites, plants and stations and the center lines for new pipelines used to transport the extracted gas. The Pennsylvania state permits database was used to identify sites and classify them COG or UOG. A complete description of the methodology used to collect the disturbance footprint of the oil and gas activity in Pennsylvania can be found in Slonecker, Milheim, Roig-Silva, and Fisher (2012).

The NLCD land cover data (Homer et al., 2015) were used as the baseline to quantify forest fragmentation attributable to COG and UOG development (see Slonecker, Milheim, Roig-Silva, & Fisher, 2012). The disturbance footprint (vector) was then used to conditionally select pixels in the 2001 NLCD (raster) to reclassify as a new class: oil and gas extraction disturbance. An updated version of the 2001 NLCD with the oil and gas extraction disturbance of 2004–2010 was created.

A series of landscape metrics were calculated for each county and for each sub-watershed intersecting the counties. These metrics were calculated for the periods prior to and following 2004–2010. Metrics included percent forest coverage, number of forest patches, average (mean) size of forest patch, percent interior forest and percent edge forest, and were calculated using the Analytical Tools Interface for Landscape Assessment (AtTILA) (Ebert & Wade, 2004).

Percent forest coverage is defined as percent of reporting unit that is in forest land cover classes; number of forest patches is defined as the number of contiguous forest cover patches (i.e. contiguous groupings of forest class pixels) within the reporting unit; average (mean) size of forest patch is defined as the average (mean) size of contiguous forest patches within the reporting unit; percent interior forest is defined as the percentage of the reporting unit that is forest class pixels at a user-defined distance from a forest edge and percent edge forest is defined as the percentage of reporting unit that is in forest land cover classes adjacent to non-forest land cover pixels. Edge forest is defined in grid cells, and a default value of 7 was used in AtTILA to calculate this metric; as the grid (re-sampled NLCD 2001) was set to 10 m, edge forest is defined to be 70 m from the boundary between forest and non-forest land cover patches. The AtTILA reporting units in this case were the counties and the sub-watersheds. The fragmentation metrics were calculated for the original NLCD 2001 land cover/land use map and the updated version with the oil and gas development footprint embedded. The change between the two time frames was calculated for all the computed metrics.
The counties and sub-watersheds were ranked based on changes in the metrics.

The ranking system developed assigns a high numerical value to areas with the least amount of change in forest, and a lower numerical value to areas with the highest change in forest. Each metric was ranked; if more than one value has the same rank, the mean rank was assigned. The ranks were then summed and equally weighted to create the final score; lower scores indicate larger changes in forest metrics, whereas higher scores indicate smaller changes.

3. Results

For the 2004–2010 timeframe, there are a total of 1632 individual UOG sites, and 11,204 COG sites. The total area for UOG sites is about 37 km² and for COG sites about 57 km² (Slonecker, Milheim, Roig-Silva, & Fisher, 2012). The total area of UOG and COG disturbance together is about 85 km²; many sites were associated with both types of development and so the total area is not the sum of both types. The typical size of an individual site is relatively small, about 0.5 ha for COG development sites and about 2.5 ha for UOG development. COG sites tend to be concentrated in the western portion of the study area and UOG sites in the southwestern and northeastern portions of the study area (Figure 2).

Of the 35 counties analyzed in this study, Forest County in northwestern and Green County southwestern Pennsylvania had the lowest scores (forests were most affected by oil and gas activities during 2004–2010; Table 1). Although Forest County is not the county with the highest number of sites, the location of the activities creates a substantial impact. For example, while Greene County has about half the number of sites compared to Forest County (663 sites and 1393 sites, respectively), Greene County has the same score. While Greene County had the largest decrease in forest cover due to oil and gas extraction activities, Forest County had the greatest changes in forest edge and forest interior percentages. McKean County has the highest number of sites, however, it had a decrease of 0.40% (or about 1019 ha) of forest coverage and had the forth lowest score.

Of the 35 counties analyzed, 16 counties had no measured change in percent forest coverage. These counties include Cambria, Wyoming, Centre, Butler, Clinton, Beaver, Somerset, Cameron, Bedford, Luzerne, Sullivan, Blair, Wayne, Huntingdon, Columbia and Lackawanna Counties. While these counties did not have any measured change in percent forest coverage, some of the other metrics did show change. For example, Luzerne, Sullivan, Beaver, Cameron, Clinton, Somerset, Wyoming, Bedford, Centre, Butler and Cambria Counties show changes in the number of forest patches. Counties like Blair, Wayne, Huntingdon and Columbia show changes in the average size of forest patch (Table 1 – presented in m² and ha), with Lackawanna County the only county with no measured change in percent forest coverage or any of the other metrics calculated. Elk County had the greatest change in number of forest patches with 99 patches, followed by Lycoming, Cambria, Butler, Centre and Bedford Counties. Forest County had the highest change in

![Figure 2. Distribution of COG and UOG permits in Pennsylvania.](image-url)
| County                | Publication                                             | Area (ha) | No. sites (within county boundary) | Change in percent forest | Forest loss (ha) | Ranking based on change of percent forest | Change in number of forest patches | Ranking based on change of number of forest patches | Change in percent forest edge | Change in percent forest interior | Ranking based on change of percent interior forest | Change in average size of forest patch (m²) | Change in Average Size of Forest Patch | Ranking Based on Change in Average Size of Forest Patch Score |
|----------------------|---------------------------------------------------------|-----------|-----------------------------------|--------------------------|-----------------|------------------------------------------|-----------------------------------|-----------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|----------------|----------------------------------------------------------------|
| Forest County        | Milheim, Slonecker, Roig-Silva, Winters, and Ballew (2014) | 110,902   | 1293                              | −0.50                    | −554.51         | 3.5                                       | 1.40                              | 25.0                              | 1.50                          | 1.0                           | −2.40                          | −6.70                          | −6.7000                  | 7.0                                                                     |
| Greene County        | Slonecker, Milheim, Roig-Silva, and Fisher (2012)       | 149,751   | 663                               | −0.80                    | −1198.01         | 1.0                                       | 9.10                              | 12.0                              | 0.90                          | 4.5                           | −2.00                          | 3.0                           | −3.00                     | 17.0                                                                     |
| Washington County    | Slonecker, Milheim, Roig-Silva, and Malizia (2012)      | 223,378   | 949                               | −0.40                    | −893.51          | 7.0                                       | 9.86                              | 10.0                              | 0.40                          | 11.0                          | −1.00                          | 9.0                           | −7.50                     | 4.0                          |
| McKean County        | Milheim et al. (2014)                                   | 254,804   | 3441                              | −0.40                    | −1019.21         | 7.0                                       | 3.30                              | 17.0                              | 1.40                          | 2.0                           | −2.10                          | 2.0                           | −3.30                     | 14.0                          |
| Westmoreland County  | Milheim, Slonecker, Roig-Silva, and Malizia (2013c)     | 268,170   | 1658                              | −0.30                    | −804.51          | 9.0                                       | 8.15                              | 14.0                              | 0.50                          | 9.0                           | −1.00                          | 9.0                           | −5.20                     | 9.0                          |
| Armstrong County     | Milheim, Slonecker, Roig-Silva, and Malizia (2013a)     | 171,889   | 1912                              | −0.50                    | −859.44          | 3.5                                       | 9.42                              | 11.0                              | 0.90                          | 4.5                           | −1.70                          | 4.5                           | −1.30                     | 28.0                          |
| Fayette County       | Slonecker, Milheim, Roig-Silva, and Malizia (2013a)     | 206,372   | 1502                              | −0.50                    | −1031.86         | 3.5                                       | 9.95                              | 9.0                               | 0.50                          | 9.0                           | −1.20                          | 7.0                           | −1.50                     | 25.0                          |
| Indiana County       | Milheim et al. (2013a)                                  | 216,674   | 1875                              | −0.50                    | −1083.37         | 3.5                                       | 8.71                              | 13.0                              | 0.90                          | 4.5                           | −1.70                          | 4.5                           | −1.30                     | 28.0                          |
| Elk County           | Milheim et al. (2014)                                   | 215,879   | 702                               | −0.20                    | −431.76          | 11.0                                      | 99.00                             | 1.0                               | 0.50                          | 9.0                           | −0.80                          | 11.0                          | −1.70                     | 22.0                          |
| Clarion County       | Milheim et al. (2014)                                   | 156,261   | 900                               | −0.20                    | −312.52          | 11.0                                      | 3.17                              | 18.0                              | 0.30                          | 12.5                          | −0.60                          | 12.0                          | −8.10                     | 3.0                          |
| Jefferson County     | Milheim et al. (2014)                                   | 169,713   | 1330                              | −0.40                    | −678.85          | 7.0                                       | 4.33                              | 16.0                              | 0.90                          | 4.5                           | −1.50                          | 6.0                           | −1.10                     | 30.5                          |
| Lycoming County      | Slonecker et al. (2013)                                 | 321,681   | 93                                | −0.10                    | −321.68          | 16.0                                      | 83.00                             | 2.0                               | 0.10                          | 18.5                          | −0.20                          | 19.0                          | −3.80                     | 12.0                          |
| County            | Authors (Year)                  | Total Population | Median Age | Mean Age | Standard Deviation | Max Difference | Average Difference | Median Difference | Average Age Difference |
|-------------------|--------------------------------|------------------|------------|---------|--------------------|----------------|---------------------|-------------------|-----------------------|
| Clearfield County | Slonecker, Milheim, Roig-Silva, and Winters (2014) | 299,025          | 16.0       | 2.08   | 12.0              | -0.50          | 13.0                | -6.80             | 6.0                   |
| Allegheny County  | Slonecker, Milheim, Roig-Silva, and Winters (2014) | 192,229          | 16.0       | 1.08   | 18.5              | -0.30          | 15.0                | -8.60             | 2.0                   |
| Warren County     | Milheim et al. (2013a)          | 231,022          | 16.0       | 2.29   | 20.0              | -0.20          | 19.0                | -4.50             | 11.0                  |
| Tioga County      | Slonecker, Milheim, Roig-Silva, and Fisher (2012) | 294,398          | 16.0       | 3.16   | 19.0              | -0.30          | 18.5                | -2.90             | 18.0                  |
| Bradford County   | Slonecker, Milheim, Roig-Silva, and Malizia (2012) | 299,761          | 16.0       | 3.16   | 19.0              | -0.30          | 18.5                | -2.90             | 18.0                  |
| Susquehanna County| Slonecker et al. (2013a)        | 214,901          | 16.0       | 1.69   | 24.0              | -0.20          | 19.0                | -5.10             | 10.0                  |
| Cambria County    | Slonecker et al. (2014)         | 179,138          | 16.0       | 1.39   | 26.0              | -1.00          | 9.0                 | -1.10             | 30.5                  |
| Wyoming County    | Slonecker, Milheim, Roig-Silva, and Malizia (2013b) | 105,225          | 16.0       | 1.39   | 26.0              | -1.00          | 9.0                 | -1.10             | 30.5                  |
| Centre County     | Slonecker et al. (2014)         | 287,872          | 16.0       | 5.0    | 36.0              | -0.20          | 19.0                | -1.40             | 26.0                  |
| Butler County     | Roig-Silva, Slonecker, Milheim, and Malizia (2013) | 204,720          | 16.0       | 4.0    | 37.0              | -0.20          | 19.0                | -1.40             | 26.0                  |
| Potter County     | Milheim et al. (2014)           | 280,239          | 16.0       | 1.37   | 27.0              | -0.30          | 15.0                | -1.30             | 28.0                  |
| Clinton County    | Slonecker et al. (2014)         | 231,960          | 16.0       | 2.00   | 18.5              | -0.20          | 19.0                | -1.70             | 22.0                  |
| Beaver County     | Roig-Silva et al. (2013)        | 114,488          | 16.0       | 2.00   | 22.5              | 0.00           | 30.0                | -7.10             | 5.0                   |
| Somerset County   | Milheim et al. (2013c)          | 279,270          | 16.0       | 3.0    | 12.0              | -2.30          | 23.0                | -2.300            | 20.0                  |
| Cameron County    | Milheim et al. (2014)           | 103,551          | 16.0       | 2.00   | 22.5              | 0.00           | 30.0                | -3.60             | 13.0                  |
| Bedford County    | Slonecker et al. (2014)         | 262,196          | 16.0       | 6.0    | 28.0              | -1.00          | 23.0                | -1.00             | 32.0                  |
| Luzerne County    | Slonecker et al. (2014)         | 235,697          | 16.0       | 1.00   | 29.5              | 0.00           | 30.0                | -3.20             | 15.0                  |

(Continued)
| County         | Publication                        | Area (ha) | No. sites (within county boundary) | Change in percent forest loss (ha) | Ranking based on change of percent forest | Change in number of forest patches | Change in percent forest edge | Ranking based on change of percent forest edge | Change in percent forest interior | Ranking based on change of percent forest interior | Change in average size of forest patch (m²) | Change in Average Size of Forest Patch (ha) | Ranking Based on Change in Average Size of Forest Patch Score |
|----------------|------------------------------------|-----------|------------------------------------|-----------------------------------|------------------------------------------|-----------------------------------|-----------------------------|------------------------------------------|------------------------------------------|------------------------------------------|--------------------------------------------|-------------------------------|---------------------------------------------------------------|
| Sullivan County| Slonecker et al. (2013b)           | 116,652   | 8                                  | 0.00                              | 0.00                                    | 27.5                              | 0.00                        | 29.5                                     | 0.00                                     | 30.0                                     | −3.10                                      | −3,1000                          | 16.0                                          |
| Blair County   | Slonecker et al. (2013a)           | 136,027   | 3                                  | 0.00                              | 0.00                                    | 27.5                              | 0.00                        | 33.0                                     | 0.00                                     | 29.0                                     | −1.70                                      | −1,7000                          | 22.0                                          |
| Wayne County   | Milheim, Slonecker, Roig-Silva, and Malizia (2013b) | 195,222   | 5                                  | 0.00                              | 0.00                                    | 27.5                              | 0.00                        | 33.0                                     | 0.00                                     | 29.0                                     | −1.60                                      | −1,6000                          | 24.0                                          |
| Huntingdon County | Slonecker et al. (2014)           | 231,146   | 4                                  | 0.00                              | 0.00                                    | 27.5                              | 0.00                        | 33.0                                     | 0.00                                     | 29.0                                     | −0.80                                      | −0,8000                          | 33.0                                          |
| Columbia County | Slonecker et al. (2014)           | 127,206   | 2                                  | 0.00                              | 0.00                                    | 27.5                              | 0.00                        | 33.0                                     | 0.00                                     | 29.0                                     | −0.20                                      | −0,2000                          | 34.0                                          |
| Lackawanna County | Milheim et al. (2013b)           | 119,789   | 1                                  | 0.00                              | 0.00                                    | 27.5                              | 0.00                        | 33.0                                     | 0.00                                     | 29.0                                     | 0.00                                      | 0,0000                           | 35.0                                          |
percent edge forest with a 1.5 % increase, followed by McKean, Armstrong, Greene and Indiana Counties. Forest County also had the highest decrease in percent interior forest (−2.4%) followed by McKean, Greene and Armstrong Counties. Wyoming County had the highest change in average size of forest patch (−9.2 m², −0.0009 ha) followed by Wyoming, Allegheny, Clarion and Washington Counties.

At the sub-watershed level, South Branch Tionesta Creek – Tionesta Creek sub-watershed had the lowest score (See supplementary material for table). This sub-watershed is located between Warren, McKean, Forest and Elk Counties. Although it was not the sub-watershed with the greatest degrees of change in its separate metrics, South Branch Tionesta Creek’s sub-watershed metrics together reported an increase in the number of forest patches (+22), an increase in percent edge forest (+3.8%), a decrease in the percent interior forest (−1.3%) and a decrease in average size of forest patch (−1,280,000 m², −128.0 ha).

Pumpkin Run sub-watershed in Greene County had the largest decrease in percent of forest coverage with a decrease of 5.1% (or about 76.6 ha). About 49% of the 929 sub-watersheds analyzed in the study showed no measured change in percent of forest coverage. The largest increase in the number of forest patches occurred in Blacklegs Creek sub-watershed, located in Indiana County, with a total increase of 234 forest patches. About 58%, or 518, of the 929 sub-watersheds studied, showed no measured change in number of forest patches.

Quaker Run-Allegheny River sub-watershed had the greatest change in percent interior forest and percent edge forest with a decrease of 16.2% interior forest and an increase of 10.8% edge forest. About 50% of the sub-watersheds reported no measured change in percent interior forest due to oil and gas activities, and about 49% of the sub-watersheds reported no measured change in percent edge forest for the studied period.

As for the average size of forest patch, Hammersley Fort sub-watershed between Potter and Clinton Counties had the largest decrease (−4,331,000 m², −433.1 ha) in average size of forest patch; about 49% of the sub-watersheds had no measured change in average size of forest patch for the time period of the study. However, the Upper East Branch-Tunkhannock Creek sub-watershed in Susquehanna County and East Branch Hicks Run sub-watershed in Cameron County both reported increases in average size of forest patch of 9932 m² (0.9932 ha) and 33,971 m² (3.40 ha), respectively. These increases in average size of forest patch may be explained by the loss of total number of forest patches; removing smaller patches of forest in the landscape will skew the average. It was also noted that the Upper East Branch-Tunkhannock Creek sub-watershed reported a decrease in percent of forest coverage; however, this change was small and with the current spatial resolution of the land cover map (30 m) not measurable or supported with the data used.

4. Conclusions

From this information, we understand that the effects of oil and gas extraction are not only a matter of measuring disturbance but of understanding where the disturbance is occurring. Previous work suggests (Slonecker, Milheim, Roig-Silva, & Fisher, 2012) that it is difficult to separate the effects of COG and UOG in forested areas of Pennsylvania because conventional extraction has occurred for several decades and sites may be co-located. Our analysis concentrates on the combined effects of COG and UOG extraction during the period of 2004–2010. The geography of change in land cover and land use is as important as the changes themselves. As shown, the counties with the greatest number of sites are not necessarily the counties with the most change, nor do changes in percent forest coverage alone necessarily show all the effects that oil and gas disturbance may have on the landscape.

Software

Data collection was performed using Esri ArcGIS 9.1 through ArcGIS10. The AToILA was used in ArcView 3.2. Microsoft Excel was used to sort and organize the data into the ranking system. Maps were generated using Esri ArcMap 10. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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