Environmental Change & Impact Due to Marcellus Well Pad Drilling:

Lycoming & Washington Counties, Pennsylvania

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Abstract:

Pennsylvania has experienced a resurgence in oil and gas exploration and production over the past two decades, mainly due to technical advances in completion and extraction methods (hydraulic fracturing). The vast majority of the 12,000+ unconventional wells target the Marcellus Shale, a primary petroleum source and reservoir rock in the Appalachian Basin. Early drilling first utilized vertical wells, followed by single horizontal wells and now finally "pad-drilling," where multiple wells and their lateral legs branch out from a common well pad. The advantages of this latest form of drilling include a reduction in operation cost as the rig and completion equipment require less transit and setup time. Additionally, surface disturbance can be minimized as the total footprint of the well areas are consolidated and less access roads and infrastructure are needed. This study focuses on wells in two counties with differing general land use: 1) Lycoming County, mostly forest and woodland and 2) Washington County, with more cultivated and developed land. Mapping the well locations and land use changes over several time intervals since horizontal drilling began, this analysis indicates that on a per well basis, less area is being altered due to oil and gas activity. This investigation quantifies the change in land type and amount over time near well pads, calculates production per disturbed well pad area, and identifies correlations among geographical factors for pad placement, such as slope and proximity to infrastructure. Objectively, this

study provides insight concerning the intensity of environmental impact as a natural resource is developed.

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1. Introduction:

Following technical advances in exploration, drilling, and especially the completion (hydraulic fracturing or fracking) of oil and gas wells over the last two decades, over 12,000 unconventional natural gas wells have been drilled in Pennsylvania alone. Most of these wells have targeted the Marcellus Shale, a primary source rock in the Appalachian Basin. Exploration and production have evolved from early vertical wells to horizontal wells and finally “pad-drilling,” where multiple wells and their lateral legs branch out from a common well pad. The advantages of this latest form of drilling include a reduction in operation cost as the rig and completion equipment require less transit and setup time. Additionally, surface disturbance is minimized as the total footprint of the well areas are consolidated and less access roads and infrastructure are needed. In particular, this analysis will compare well pads in two counties with differing general land use: 1) Lycoming County, mostly forest and woodland and 2) Washington County, with more developed vegetation and human use land. The main objectives of this study are to assess changes in land cover type near well pads, identify correlations of geographic factors, and verify that production per unit disturbed area on well pads have increased.

2. Goals & Objectives:

With over twelve years of drilling activity, the trend towards higher multi-well pads, and the differing geographic characteristics in both counties, three main goals have been selected to study the environmental impact of the Marcellus Shale development. First, we determine changes in land cover type and the amount over time near well pads. Second, we assess natural gas production per unit disturbed area on the well pad will be assessed to verify if production efficiencies have improved over time. Third, this study seeks to identify any correlations among geographic factors and well pad placement, such as the slope of the terrain, proximity to infrastructure, and soil type. Ideally, these findings could serve as a tool or model for oil and gas operators and conservationist in monitoring the impact of drilling and addressing environmental concerns.

3. Background:

The Marcellus Shale is a black shale with interbedded limestone that was deposited in a shallow marine environment in what is now the Appalachian Basin of the eastern United States. The formation is Middle Devonian (~390 million years ago) in age and serves as a source rock for several overlying petroleum reservoirs. Some of the hydrocarbons produced in the Marcellus have migrated into these shallower, younger sedimentary units and it was not until the early 2000's that well drilling technology and the use of hydraulic fracturing ("fracking") made the formation a prime shale gas target. Early vertical wells explored the extent and natural gas resource potential of the Marcellus and the first horizontal wells were drilled in Pennsylvania in 2005. Since then, over 12,000 wells have been drilled across the state as of the end of 2019, with a peak in drilling during the 2011 to 2013 time interval (Figure 1). Even as drilling has slowed in recent years, a trend of increasing average number of shale gas wells placed on a well pad (the area of land where drilling and associated well work is performed) has continued since the first multi-well pads in 2008 (Figure 2). Nearly seven wells are drilled on a pad on average in 2019 with some operators drilling over twice that amount. The shale gas play, or region of prospective resource, also extends to the southwest into parts of West Virginia, and to the northeast in southern New York. While well drilling and fracking occurs in West Virginia, New York initially instituted a moratorium and has since 2015 banned the process (NYS 2015).

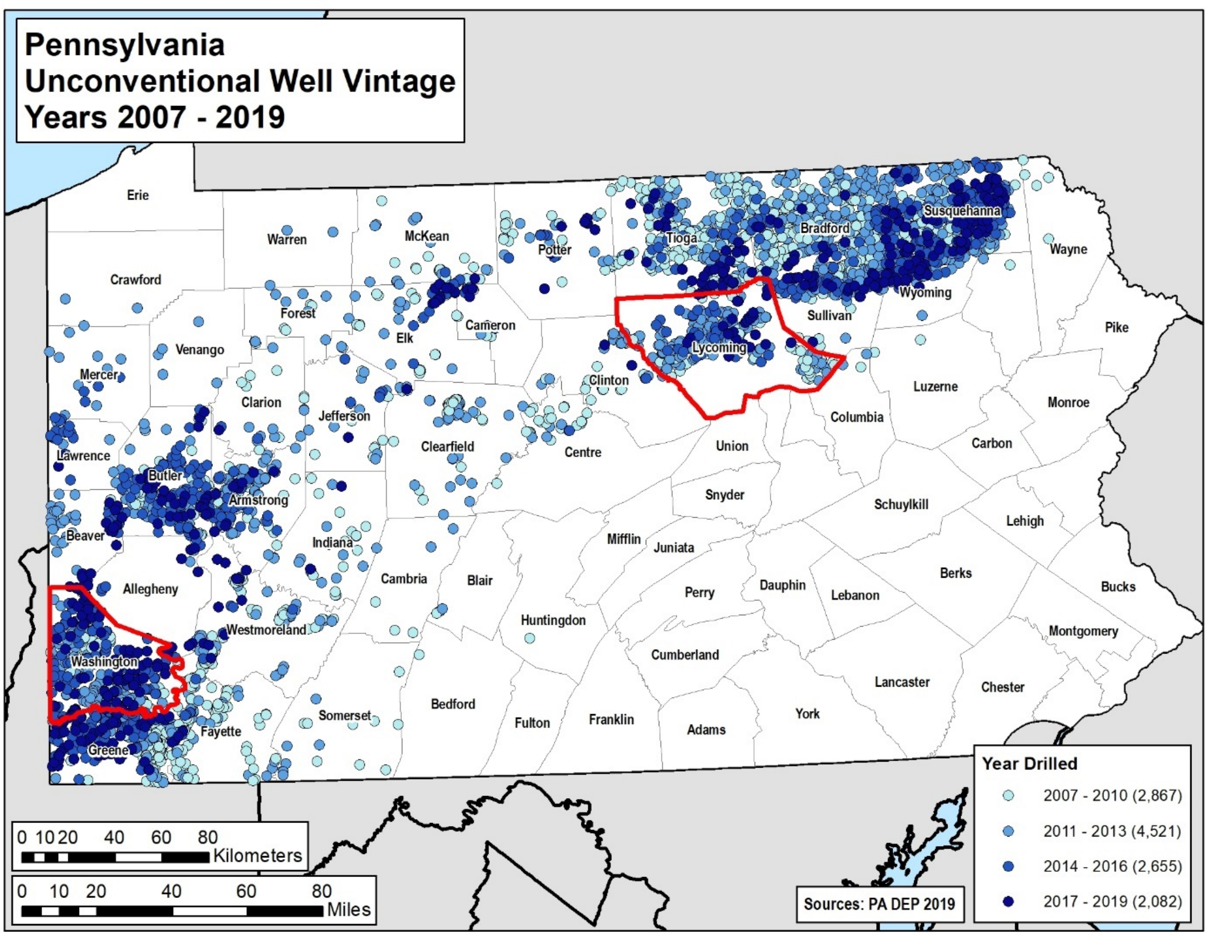

Figure 1. Distribution of Marcellus Shale unconventional wells drilled in Pennsylvania (2007 – 2019).

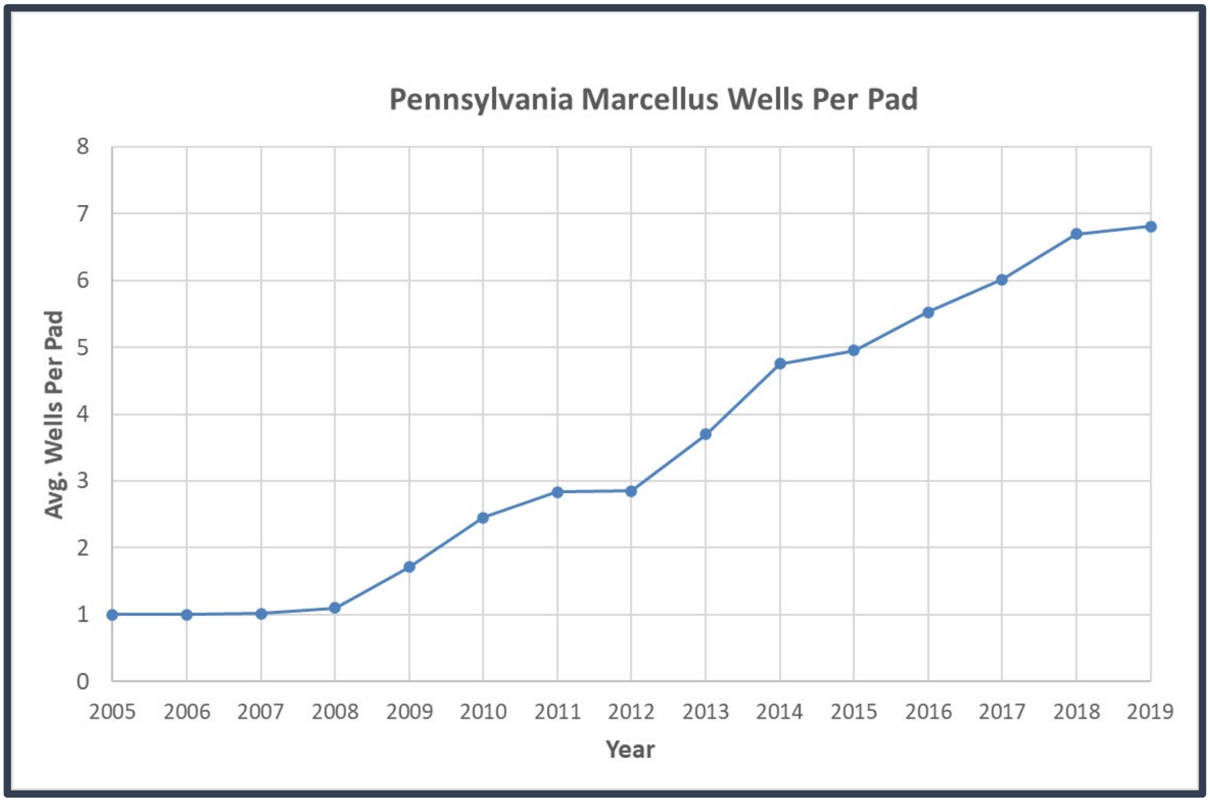

Figure 2. Average number of wells by pad for the Marcellus Shale in Pennsylvania (2005 – 2019).

In terms of geologic characteristics, the prospective region of the Marcellus Shale is found at sub-surface depths of near 3,000 ft to over 9,000 ft in Pennsylvania, generally dipping from the northwest to the southeast until the unit again becomes shallower along the Appalachian Mountains' western edge (Figure 3). The gross isopach, or formation thickness, of the shale ranges from less than 25 ft to over 700 ft in the state, with thicker areas towards the northeast (Figure 4). Generally, deeper areas can have higher natural gas potential and recovery due to pressure (up to a certain point), although wells become more costly and difficult to drill. Thicker areas also can be more prospective as there is more volume to produce and hold hydrocarbons however rock quality (i.e., porosity, permeability, and other factors) must also be sufficient. As shown in the comparison table (Table 1), both Washington and Lycoming counties exhibit somewhat similar geologic properties, had peak well drilling years between 2011 and 2013, and average approximately four wells per well pad. Some of the main differences between the two regions in this study are area, population density, and total wells drilled. It should be noted that approximately half of Lycoming County's larger geographic extent lacks the Marcellus at prospective depth, a contributing factor to the lower number of wells.

Table 1. Geographic and well characteristic comparison of Washington and Lycoming counties.

	Washington County	Lycoming County
Region	SW PA	NE PA
Area	861 mi^2	1,244 mi^2
Population Density	243/mi^2	92/mi^2
Depth	5,000 - 7,500 ft	2,000 - 7,500 ft
Isopach (thickness)	65 - 200 ft	140 - 255 ft
Total Wells	1,496	925
Peak Well Years	2011 - 2013	2011 - 2013
Well Pads	363	234
Avg. Wells/Pad	4.1	4.0
Main Operator	Range Resources	Ard Opr LLC

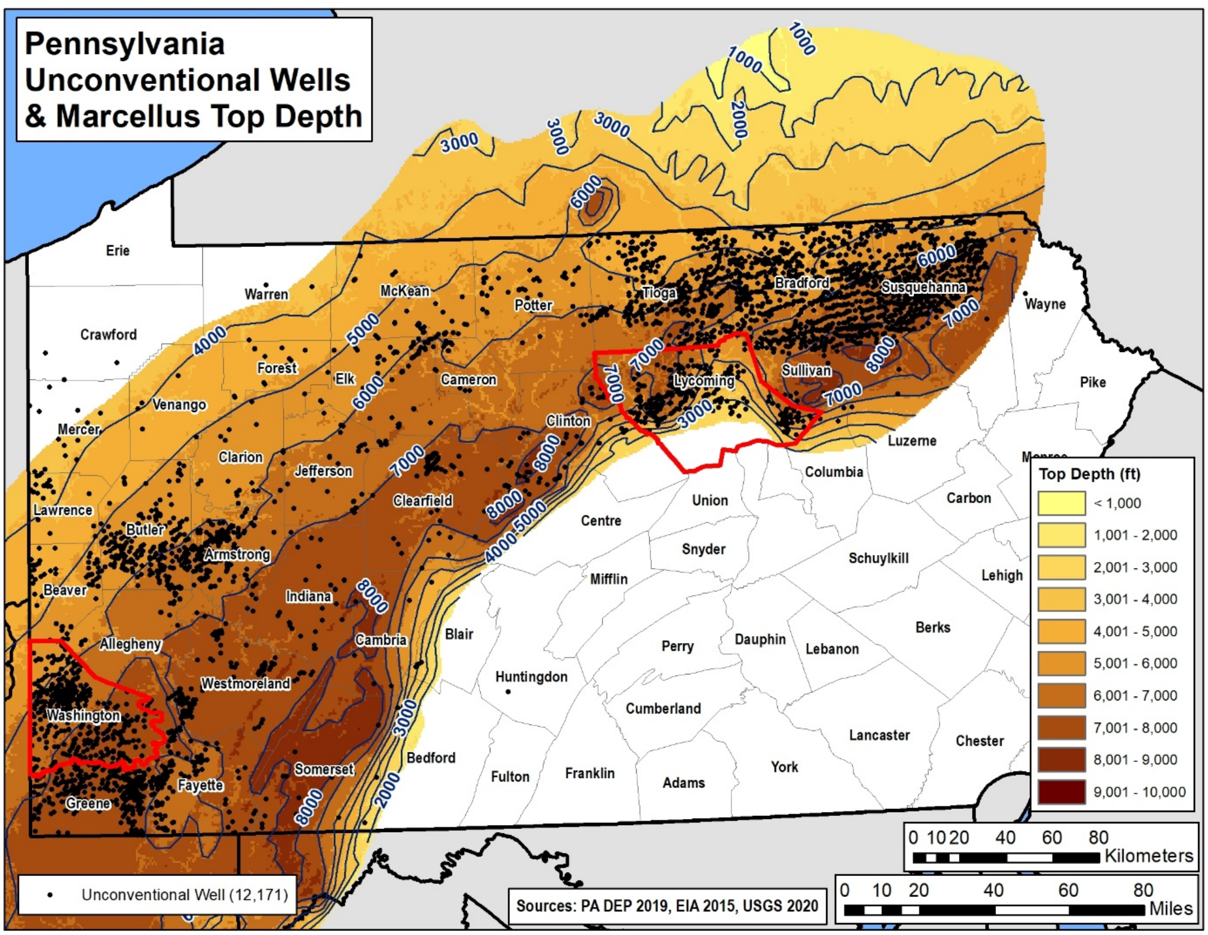

Figure 3. Sub-surface depth to the top of the Marcellus Shale (inferred from structure contours and DEM).

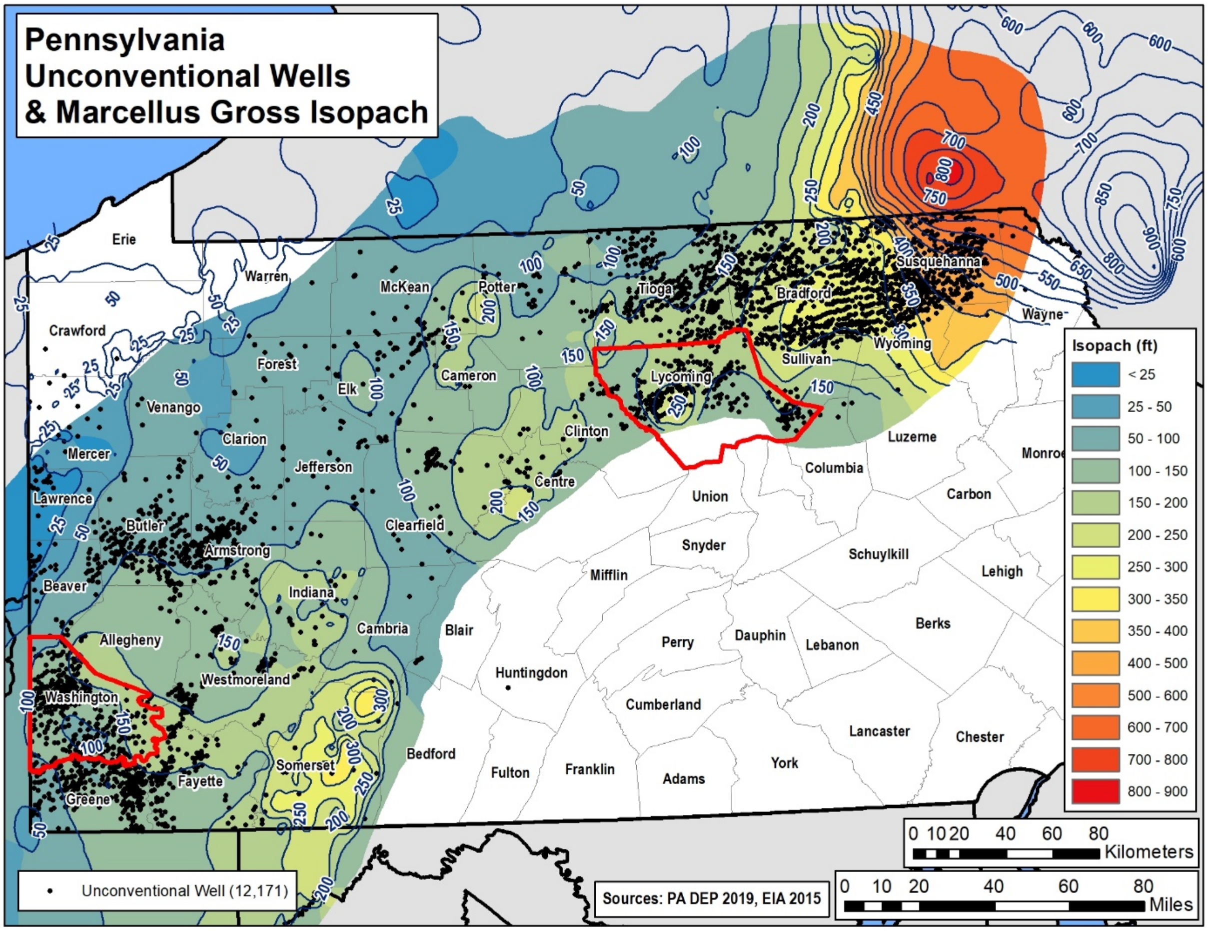

Figure 4. Gross isopach (total formation thickness) map of the Marcellus Shale.

4. Previous Studies:

Reviewing both academic literature and technical analyses, prior studies have focused on several aspects of well pad drilling and its effects. A 2010 article in *The American Oil & Gas Reporter* (Arthur et al. 2010), notes how the oil and gas industry has been reducing surface disturbance footprints with both horizontal drilling and well pads. The author cites a 2008 analysis of the Fayetteville Shale (similar to the Marcellus in Pennsylvania) describing how one vertical well in the play involves 4.8 acres of well construction and infrastructure area. A well pad that can support four to eight horizontal wells would require just 7.4 acres and also likely produce more gas on a per well basis. Gant (2011) states that in 2008, only 17% of Marcellus Shale wells were drilled on multi-well pads and that number had increased to 83% by August 2011. More recent data has also shown that the average number of wells drilled per pad has steadily increased since Marcellus development has matured, to over five wells per pad by 2013 (Hanson et al., 2016). Litvak (2018) noted that operators such as EQT and Range Resources have pads that include up to 22 drilled wells, with recent averages at around 18 and 10 wells, respectively. Operators also state that they typically have been building oversized pads to allow for future development based on economic conditions and the price of oil and gas. Clearly, there has been measurable variance in well pads over time, between operators, and geographically within the state.

Other studies have focused on methods of detecting land use change using remote sensing techniques. A report on land cover change in the Haynesville Shale region (Unger et al. 2015) utilized Landsat Thematic Mapper imagery for six years over the time period 1984 – 2011 to classify and compare land cover in and around well drilling activity using an automated process. Due to sensor resolution, the analysis yielded a fairly low user's accuracy of well pad identification (50 – 60%) and additional infrastructure such as access roads were unable to be detected (thus underestimating surface disturbance). Higher resolution National Agriculture Imagery Program (NAIP) imagery was used in a 2012 U.S. Geological Survey assessment on Bradford and Washington counties in Pennsylvania, from 2004 – 2010 (Slonecker et al. 2012). Example maps showing the GIS feature extraction process and identified disturbance are shown in Figures 5 and 6.

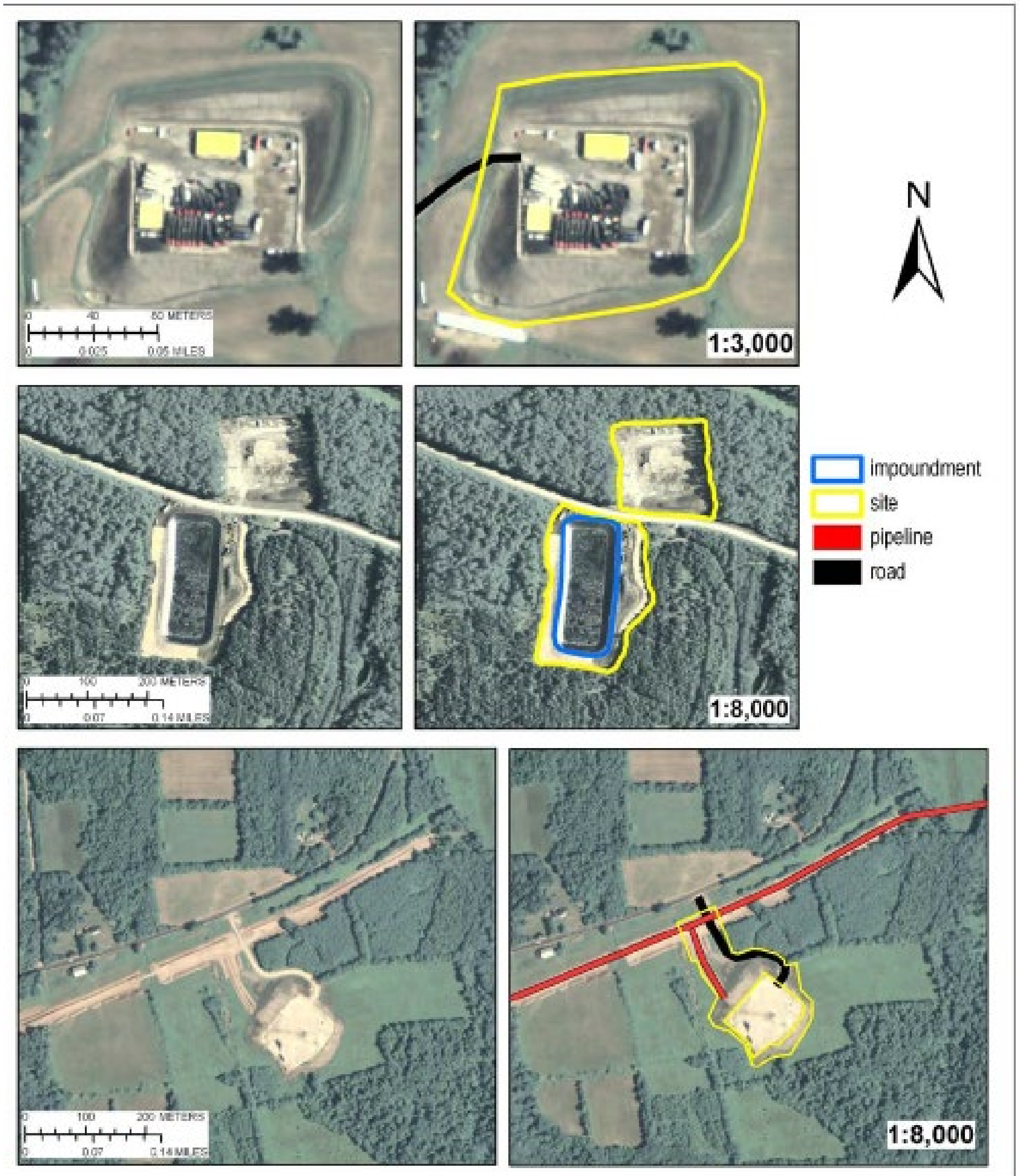

Figure 5. Average number of wells drilled per pad in the Marcellus Shale from 2005-2013 (from Slonecker et al. 2012).

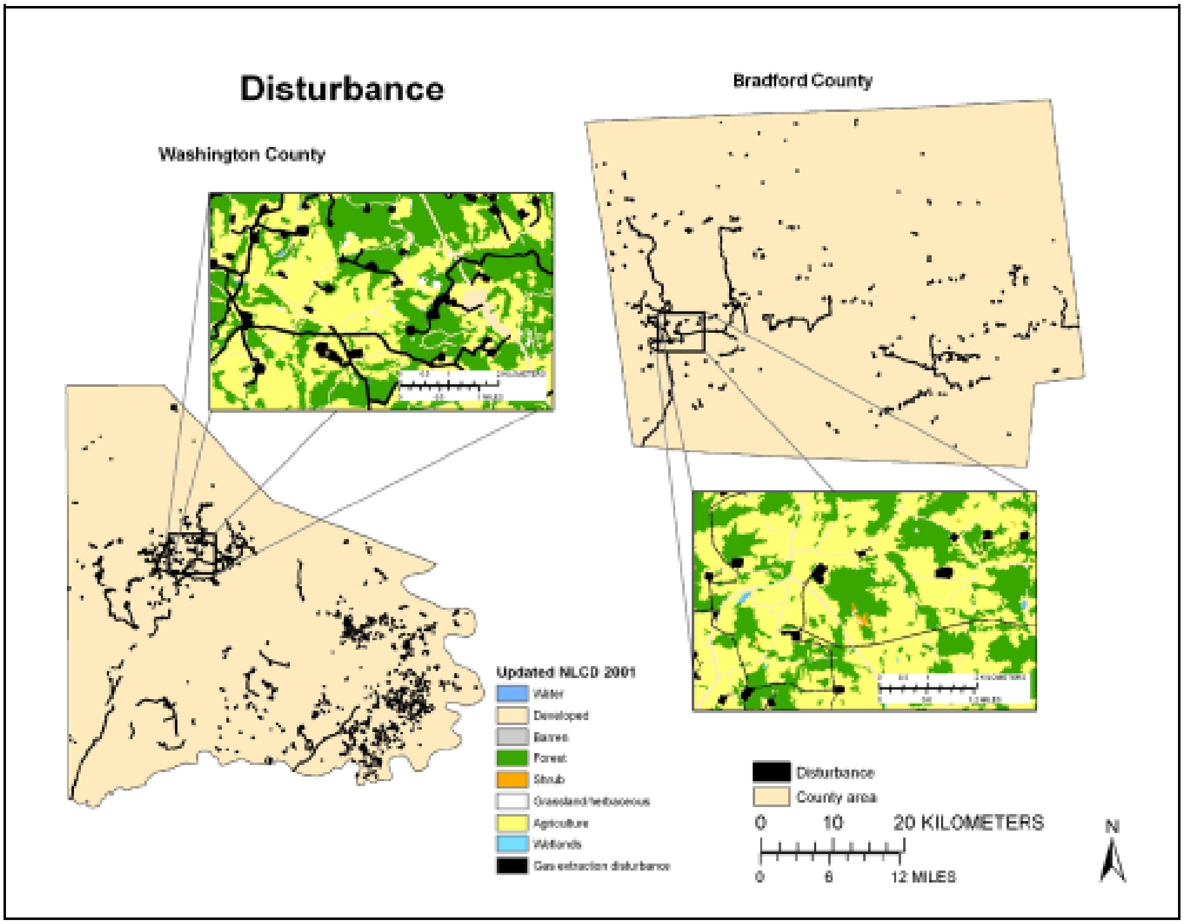

Figure 6. Gas extraction-related disturbance identified between 2004 and 2010 in Bradford and Washington Counties, Pennsylvania. (from Slonecker et al. 2012).

Looking beyond the raw land cover type in and around wells, one study focused on the habitat and species population effects of drilling, in particular aquatic communities (Keller et al. 2017). The researchers looked at key indicator species in the Susquehanna River Basin in northern Pennsylvania at streams with no, low, and moderate well pad densities. In general, no significant differences in water chemistry or animal assemblages could be effectively observed, however even the moderate well pad densities (up to 0.541 well pads/km^2) represent a least intrusive scenario for impacts. Other areas may now or in the future have higher well pad densities that could be assessed or monitored in the long term for changes. In addition, most well pads were fortunately placed on level terrain, preventing opportunities for spills and runoff events. Another study on well pad drilling focuses on drilling economics and the design and placement of wells themselves (Abramov 2019). The author uses 30 well parameters, differing oil production decline rates, and well grouping setups to determine optimal net present value (NPV) scenarios.

While the analysis is insightful on maximizing production and revenue, little if any geospatial data and modeling is required.

In addition to studying general well pad trends of the past, some research has focused on future estimates of well pads and their estimated effect on the environment. A 2016 report prepared for and funded by the Delaware Riverkeeper Network calculated the impacts of Marcellus Shale gas drilling by county in Pennsylvania should drilling exhaust the technically recoverable resources. These impacts included: land use changes, forest fragmentation, population proximity, air emissions, water withdrawals, and wastewater generation (Hanson et al. 2016). A variety of state and national datasets were incorporated (National Land Cover Database, U.S. Census Data, Pennsylvania Department of Environmental Protection, etc.) and the main output and results of the study are statewide maps showing projected effects at the county level, such as the estimated well development map in Figure 7.

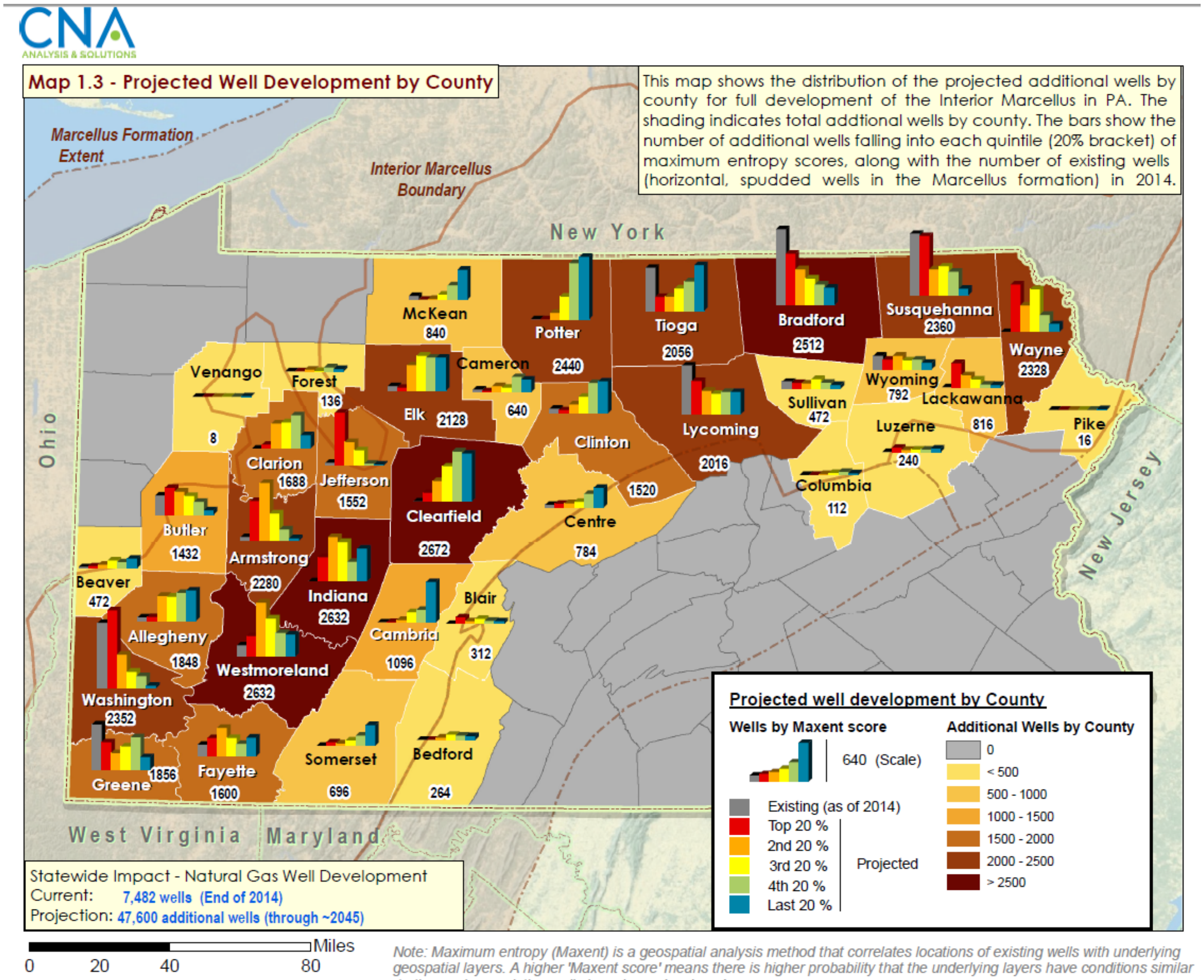

Figure 7. Projected well development by county (from Hanson et al. 2016).

5. Data Sources:

A variety of data sources and types were used in this assessment and are described in the following five subsections:

5.1 Unconventional Well Data:

Information regarding the wells and well pads in each study area was derived from the Pennsylvania Department of Environmental Protection. Such tabular data includes the surface hole locations of the wells, well pad identification (for grouping wells on a unique pad), operator name, dates of first production, and the monthly production of natural gas. A distribution of the wells is shown Figure 1.

5.2 Land Cover Data:

The National Land Cover Database (NLCD) includes five vintages of data that we utilize in studying change over time for this study (2004, 2008, 2011, 2013, and 2016). An example map of the 2016 land cover layer for Pennsylvania is shown in Figure 8 with the Marcellus unconventional wells overlain. Fifteen land cover types exist in Lycoming and Washington counties and are shown in the legend for the 2008 Lycoming County map in Figure 9. The land cover data maintains the same category types across all vintages and also keeps a standard 30 meter resolution. This resolution is sufficient to detect and calculate land cover change in and around well pads as demonstrated by the pre- and post-well development maps shown in Figure 10. Prior to the drilling of eight wells on one pad between 2011 and 2016, the left map of 2008 land cover shows the well site consisting of mostly hay/pasture land cover. By 2016, the land cover transformation can clearly be identified, changing to various intensities of developed land.

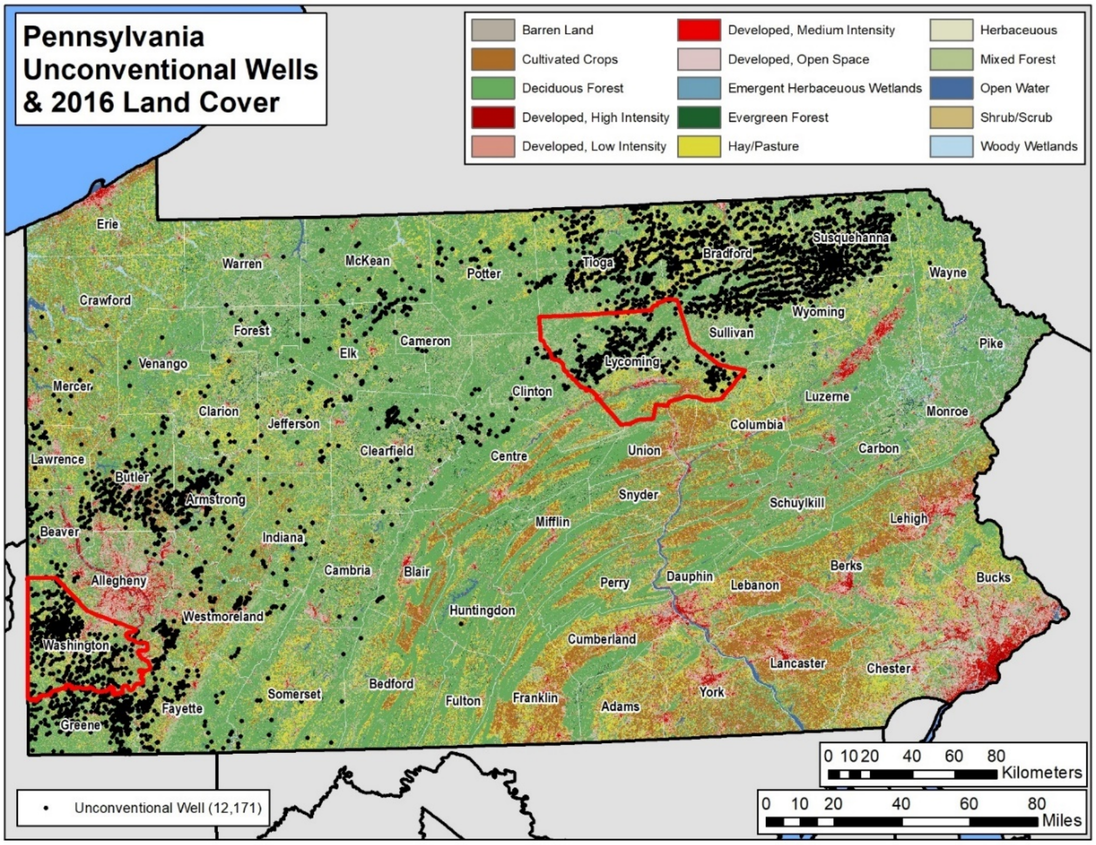

Figure 8. 2016 NLCD land cover in Pennsylvania.

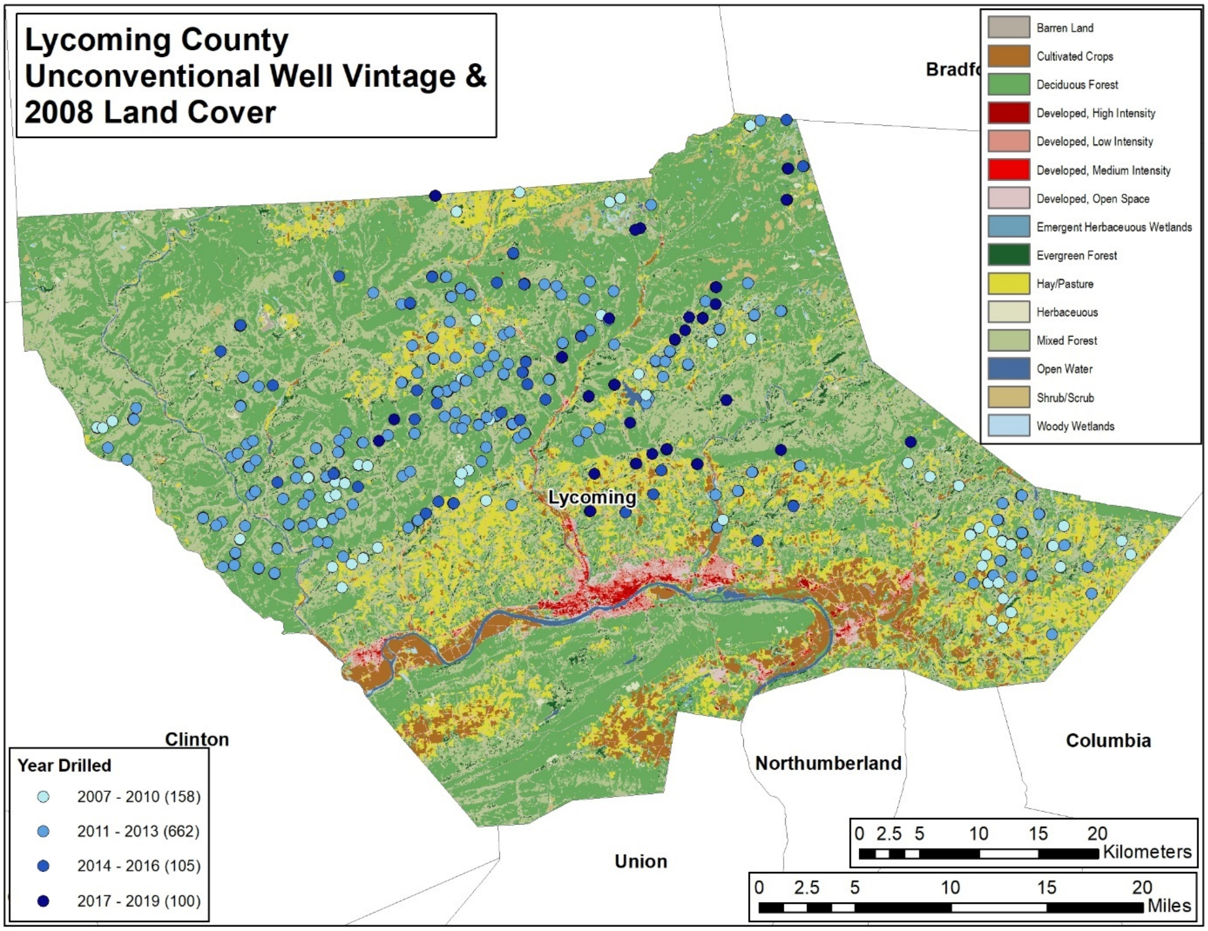

Figure 9. 2008 NLCD land cover in Lycoming County.

Figure 10. 2008 and 2016 NLCD land cover for a recent well pad in southwest Washington County.

5.3 Digital Elevation Model (DEM) Data:

Elevation data to be used in the study comes from the USGS National Elevation Dataset with a vintage of 2006. The resolution of the data is 1/9 arc second which is approximately three meters at the study area latitudes. While not detailed enough to accurately measure elevation changes on well pads due to drilling-related construction/land removal, the DEM is sufficient to calculate generalized slope (and aspect) that can be used for correlation analysis. Example maps of percent slope in both Lycoming and Washington counties are shown in Figures 11 and 12, respectively. Note that Lycoming County tends to have higher slopes and more rugged terrain.

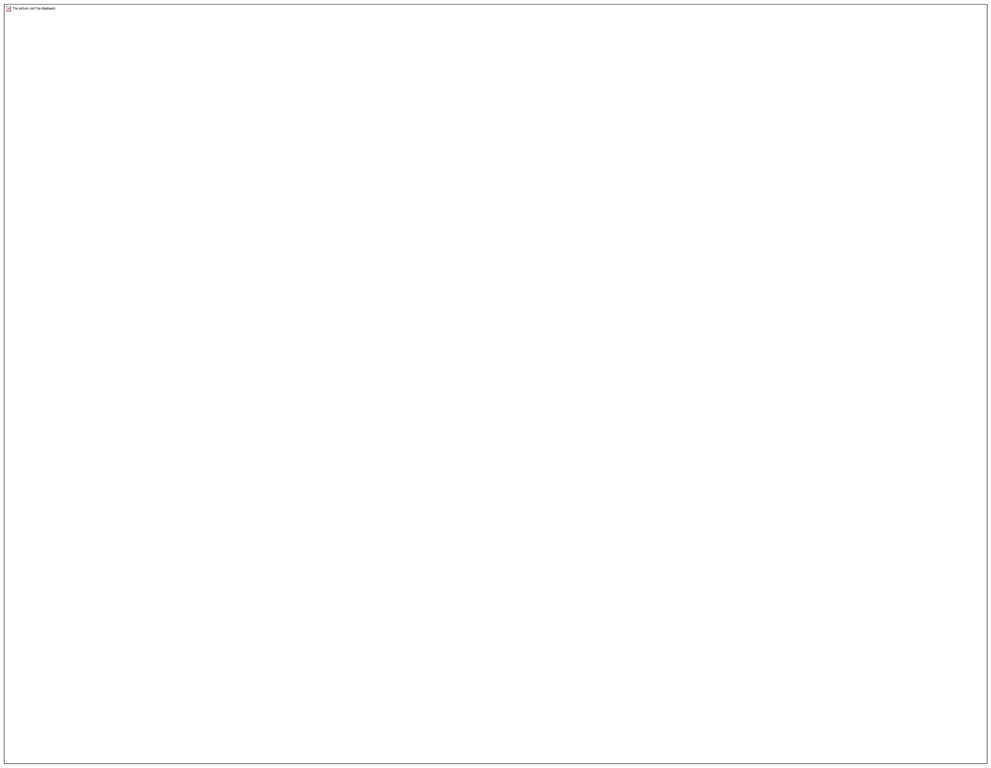

Figure 11. DEM-based slope map of central Lycoming County.

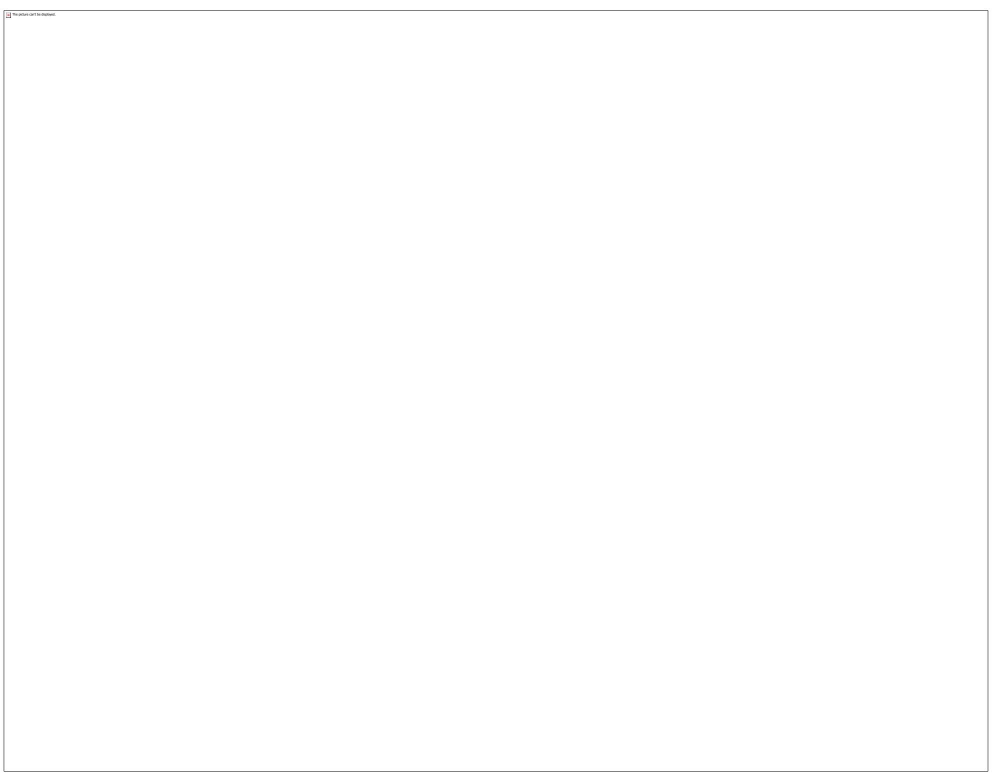

Figure 12. DEM-based slope map of southeastern Washington County.

5.4 Aerial Imagery:

Aerial imagery was also utilized to ground truth the land cover layers and ensure accuracy. The USDA's National Agricultural Imagery Program (NAIP) has recorded imagery across Pennsylvania about every three years and an example map comparing the NLCD and NAIP layers is shown in Figure 13 for the same area shown in Figure 10. The accuracy of the lower resolution land cover layer to closely match the imagery at the well pad scale proves sufficient for the scope of this study.

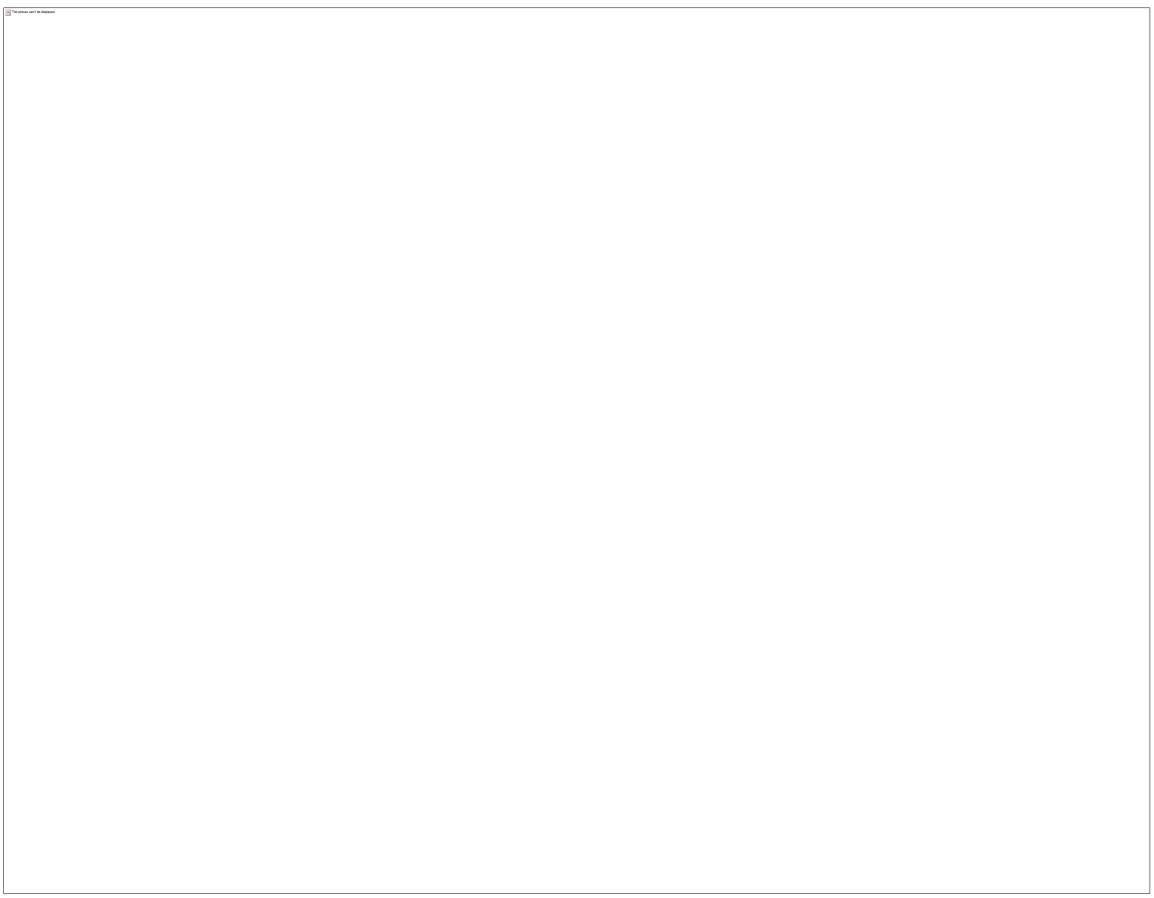

Figure 13. 2016 NLCD land cover and 2019 NAIP imagery for well pad in southwest Washington County.

5.5 Other Data:

Additional geospatial data was also processed and analyzed to determine if well pad locations are related to the presence or proximity of other features. This included proximity to local and state roads for accessibility (Pennsylvania Department of Transportation) and the relationship between well pads and soil type (USDA Soil Survey).

6. Methods:

The methodology for the study is sequential in design and followed four main steps:

1. Subset Data – Using ArcMap 10.8.1 GIS software, well pad center locations were buffered to a set radius of 150 meters so that ideally only changes due to well drilling were detected in the imagery and land cover maps. This distance was chosen based on initial data observation, essentially it is the typical maximum extent of a well pad's footprint over the surrounding area. An example map showing the pad, wells, land cover, and buffer distance is shown in Figure 14.

2. Quantify Land Change – Land cover area changes for each of the 15 classes were calculated between each land cover vintage from 2004 to 2016 by clipping each raster to the buffered well pad polygons.

3. Production – Production was computed at the well pad level by first downloading all available production data for each county's wells through the Pennsylvania Department of Environmental Protection. Using the first production date as a starting point, a Microsoft Access database summed the first three years of production for each well based on the number of days the well was producing natural gas. This method normalizes a cumulative production for each well since older wells will have been online longer than more recent wells and have typically produced more. The three year interval ensures that the latest wells drilled in 2016 have full production records as 2019 was the last complete year of production records at the time of this analysis. Next, the production at each well pad is determined from aggregating each well that shares the same well pad identification number. Finally, production efficiency is then calculated on a per unit disturbed area basis to determine if production has increased while reducing environmental impact.

4. Analyze Correlations – Trends and correlations are identified over time between both counties to include changes in each well/land cover vintage for 1) slope percentage, 2) proximity to roads, and 3) soil/farmland type.

Figure 14. 2016 NLCD land cover and 150 meter buffer example for well pad #147922 in southern Washington County.

5. Results:

The following three sub-sections describe the results of the study analysis that include 1) land cover change, 2) production, and 3) geographic factors.

1. Land Cover Change:

Due to the well pad areas being quite small in relation to the extent of the counties themselves, a set of example area maps of the two counties' land cover change are shown in Figures 15 and 16. The Washington County map (Figure 15) shows a typical field of wells with circular areas depicting the well pad and buffer. Green areas show no change in land cover from 2004 to 2016 while red areas indicate a change, usually from non-developed to developed land class. As expected, the highest amount of change in generally concentrated in the center of the pad. The Lycoming County map (Figure 16) is at the same scale and while most pads showed some change over the study interval, a significant portion had very little to no change. Surprisingly, it was found that most of these areas were already developed in some form.

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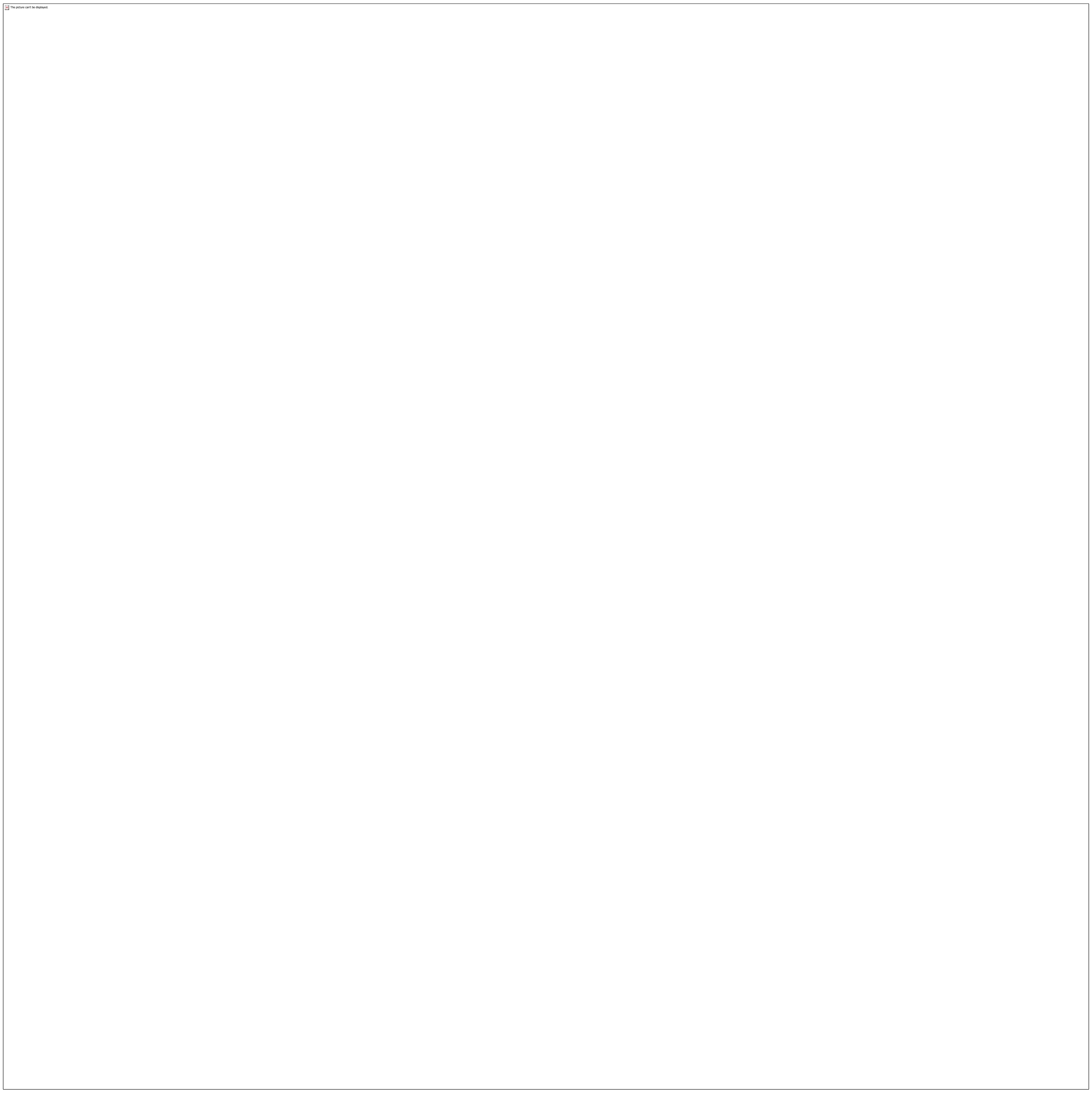

Figure 16. Lycoming County 2004-2016 land cover change within 150 meter well pad buffer areas.

Table 2 summarizes the results of the land cover change analysis within buffered well pad areas for Washington and Lycoming counties. In Washington County, 1,496 wells were drilled on 363 well pads, with a total buffered well pad area of 27.64 km^2. Using 2004 as a baseline for pre-Marcellus well drilling, there was only a 2% change in land cover area by 2008 due to limited number of new wells. This peaked to 17% land area change from 2013 to 2016. In aggregate, from 2004-2016 there was a net land cover change of 6.40 km^2 (23.2%) in Washington County.

In Lycoming, 925 wells were drilled on 234 unique well pads, giving a total buffered well pad area of 17.75 km^2. There was only a 1% change in land cover area by 2008. This increased to 7% from 2008-2011 with slightly less change over the 2013 and 2016 land cover vintages. From 2004-2016, there was a net land cover change of 2.19 km^2 (12.3%) in Lycoming County.

Table 2. Land cover change results from 2004-2016 vintages for well pad areas in Washington and Lycoming counties.

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Figures 17 and 18 break down the land cover area percentage change over time by individual type (with all four developed classes are combined as one) for Washington and Lycoming counties, respectively, from 2004 to 2016. For Washington County, the greatest positive land cover type change was that of developed land at 14.3% increase in total well pad area (3.9 km^2). The greatest negative land cover type change was that of deciduous forest (-13.0%, -3.6 km^2) and hay/pasture (-7.3%/-2.0 km^2). In Lycoming County, the greatest positive land cover type change was that of herbaceous land at 6.9% increase in total well pad area (1.2 km^2). The greatest negative land cover type change was that of deciduous forest (-4.5%, -0.8 km^2) and mixed forest (-3.8%, -0.7 km^2). Note that developed land of any type only increased 1.0%, or just 0.2 square kilometers.

Figure 17. Washington County 2004-2016 land cover area percentage change by type over well pad buffer areas.

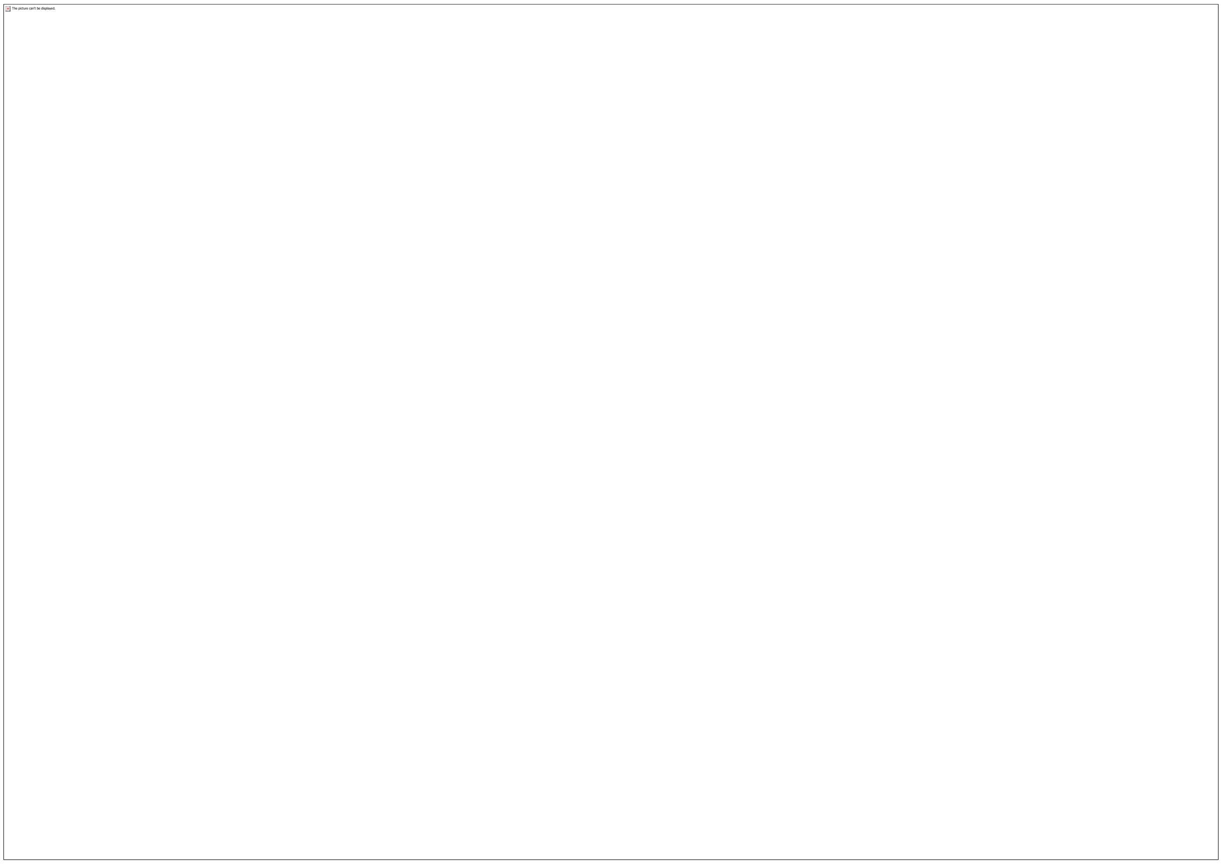

Figure 18. Lycoming County 2004-2016 land cover area percentage change by type over well pad buffer areas.

The chart in Figure 19 combines the total land cover change in each interval along with the annual average wells/pad for Washington and Lycoming counties (orange and blue, respectively). Lycoming County shows a moderate increase in land cover change in 2011 at 7% and just over three wells per pad, then flattens out to 5% change even though wells per pad increased to almost four. Washington County has a similar increase/plateau trend except land cover change jumps to 17% in 2016, though a relatively low number of wells were drilled that year.

Figure 19. 2004-2016 land cover area percentage and annual wells per pad change in Lycoming and Washington counties.

2. Production:

As described in the methodology section, production across all wells was limited to the first three years to ensure a normalized sum and enable the comparison of both old and new wells. In Washington County, 363 well pads produced over 4.0 trillion cubic feet (tcf) of natural gas from three-year wells, resulting in an average of 11.1 billion cubic feet (bcf) per pad from 4.12 wells per pad. In Lycoming County, 234 well pads produced over 2.2 tcf of natural gas from three-year wells, with an average of 9.4 bcf per pad from 3.95 wells per pad. The relationship between wells per pad and the three-year cumulative production is clearly positive in both counties as shown in Figure 20.

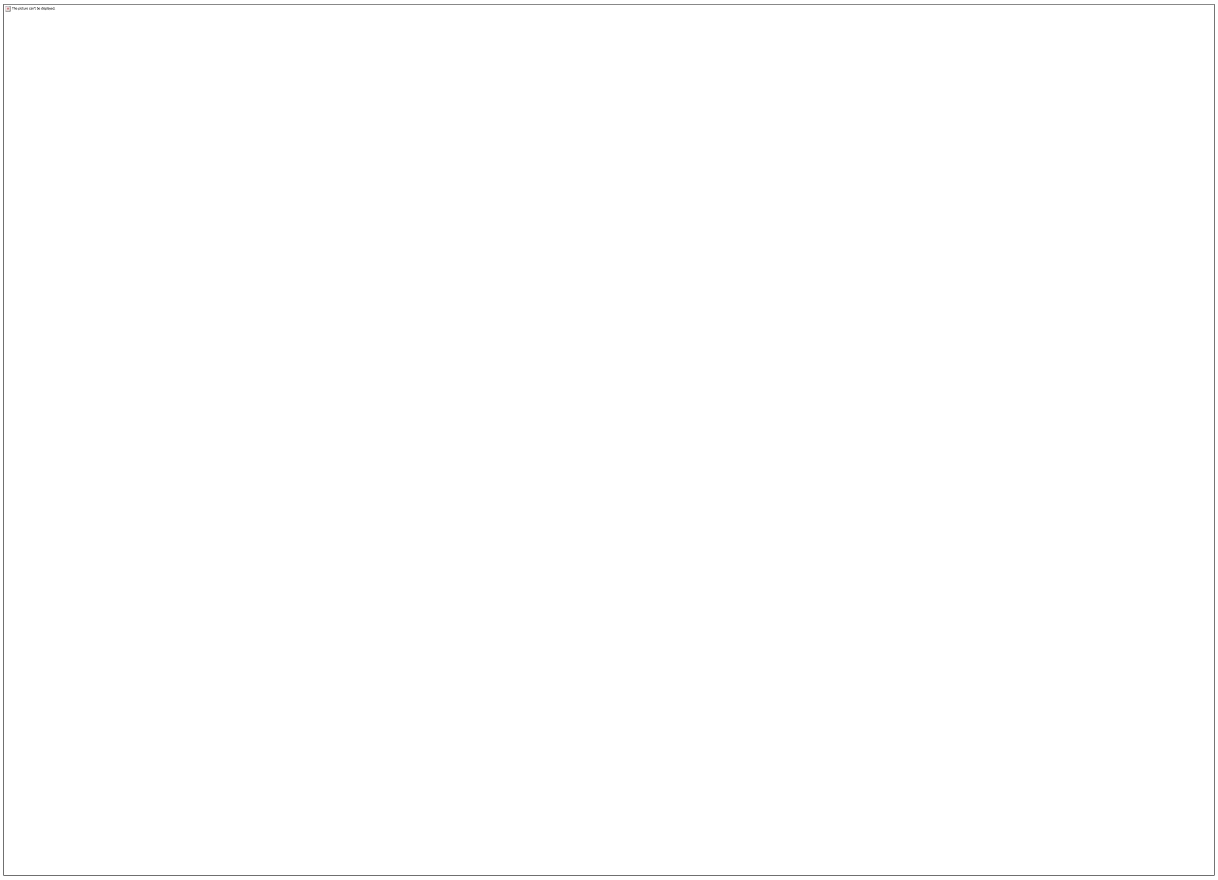

Figure 20. 3 year cumulative gas production per well pad, Lycoming and Washington counties.

In terms of production per unit disturbed area identified by land cover change, both counties show significant increases with the advent of well-pad drilling. In Lycoming County, all multi-well pad production resulted in 1,009 bcf/km^2 of land change. Using just the first well drilled on each pad, the production drops to just 241 bcf/km^2 of land change. This means that if operators were to extract the difference using separate, single well pads, there would likely be a proportionate amount of additional land cover change (such as loss of forest, increase in developed area). A similar result is found in Washington County, though at lower ratios, with a multi-well pad average of 631 bcf/km^2 versus a single well at 124 bcf/km^2. It should be noted that wells have generally become more productive over time, with longer laterals and better completion techniques, so some of this increase may not be purely due to additional wells per pad.

3. Geographic Factors:

In addition to land cover change and production, an investigation into several geographic factors was carried out to determine if any trends aligned with the number and placement of well pads over time. Figure 21 displays the number of new well pads drilled per year and the average slope (in percentage) of the well pad terrain for each group of wells by county. Washington County well pad slopes, presented as orange circles, show no real significant change in slope, hovering between 15% and 19%. Lycoming County well pad slopes, presented as blue circles, appear to show a slight decrease in slope from 17% in 2007 to just over 10% by 2015. Other than this small change, well pads in both counties appear to maintain relatively low slopes throughout the drilling history.

Figure 21. Annual new well pads and average well pad area slope, Lycoming and Washington counties.

Another geographic feature analyzed was proximity to infrastructure, specifically the distance from the well pad center to the nearest road. Figure 22 shows the number of new well pads drilled each year as compared to the average distance to the closest local or state road. Washington County road distances, presented as orange circles, show no real significant change in proximity, averaging between 250 to 350 meters. Lycoming County road distances, presented as blue circles, do show an increase in distance from less than 300 meters prior to 2010 to just over 500 meters by 2014. This could be a function of operators drilling up the highly prospective areas early on that are better accessible to infrastructure and thus less costly than the more remote regions.

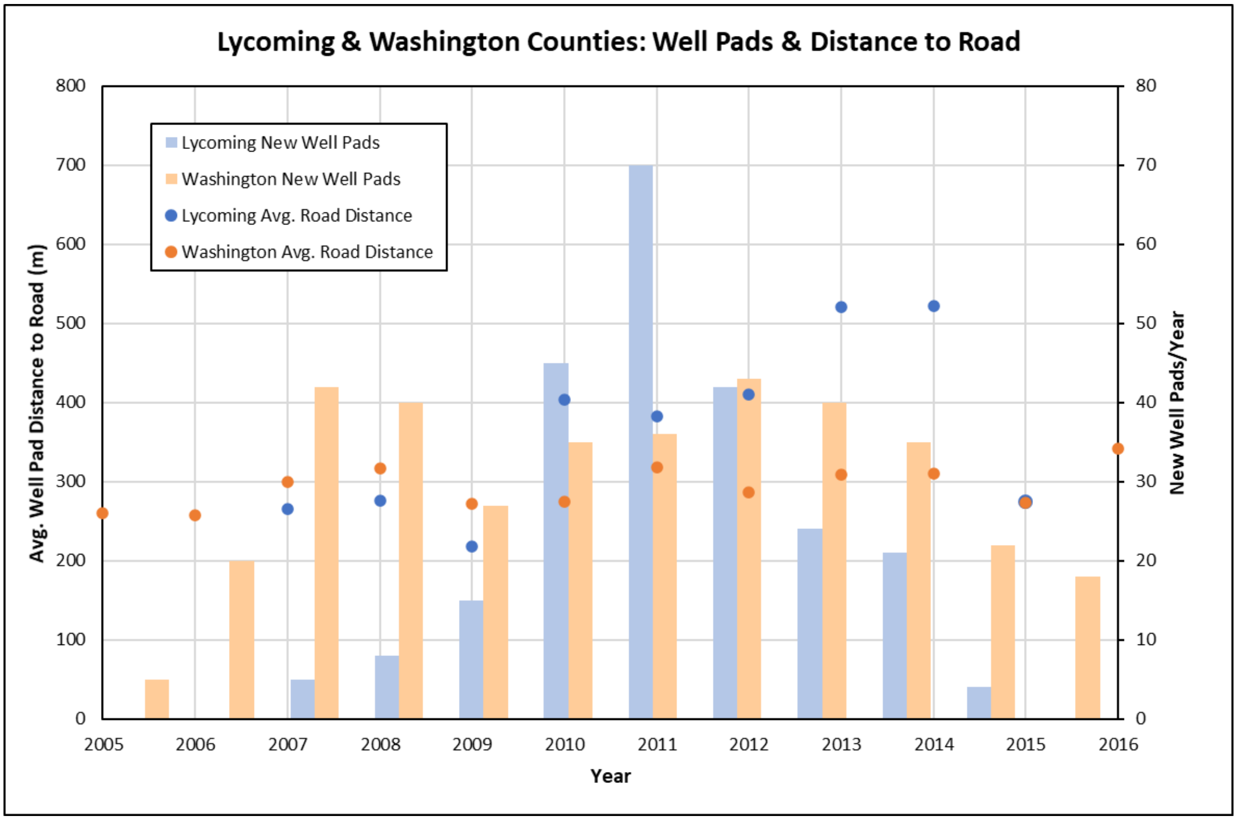

Figure 22. Annual new well pads and average well pad distance to nearest road, Lycoming and Washington counties.

The third and final factor evaluated was the relationship between soil types and well pads. Due to the complexity and multitude of soil types, this analysis was simplified in terms of farmland favorability, an attribute provided in the USDA soil survey source dataset. In Figure 23, non-prime farmland is depicted as pale blue and orange columns for Lycoming and Washington counties, respectively, while increasingly bolder hues show important farmland and then prime farmland. The average well pad area percentages are shown on the y-axis. Across all years, most of the well pad areas in both counties had been classified as non-prime farmland, and there appears to be no strong correlation over time.

Figure 23. Average well pad area distribution by farmland type, Lycoming and Washington counties.

6. Conclusion:

Based on the results of this land cover analysis, both Lycoming and Washington counties lost forest land in and around well pads while gaining developed and herbaceous land cover. However, the land change per unit production has been mitigated with pad drilling as less surface area is disturbed by drilling many wells on the same pad versus multiple separate pads. With average wells per pad across all years totaling over four wells per pad in both counties, the production per unit disturbed area has also increased by at least this factor, suggesting that multi-well drilling can maintain well production efficiency while lessening the environmental cost of direct land cover change.

It should be noted that in addition to changes in well design over time, localized differences in geology, lease configurations, and operators can affect production and well pad placement, though this is beyond the scope of this project. The application of these analysis methods could be applied to the rest of Pennsylvania (and other multi-well pad states) and also compared to future land cover assessments such as the forthcoming 2019 vintage (USGS, 2020).

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