Assessing Land Use Changes Due to Natural Gas Drilling Operations in the Marcellus Shale in Bradford County, PA

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ABSTRACT

Extraction of natural gas from the Marcellus Shale formation began in the mid-2000s, and well pads and their associated infrastructure are now prominent fixtures throughout the Appalachian region. However, there is currently little research available to provide insight into its implications for land use and land cover change. In this case study of Bradford County, Pennsylvania, we used high-resolution aerial photography, land cover data, and well point data to quantify current and potential land use change as a result of gas drilling, as well as the types of land cover to be converted. Based on the number of permits held as of October 2011, we estimate that 276.84 hectares of primarily agricultural land have been cleared for well pads, access roads, and impoundment ponds in Bradford County. If all permitted wells are developed, we estimate between 620.60 and 3,983.50 hectares of additional land use change could occur.

Key Words: Marcellus Shale, natural gas, well pad, land cover change, Bradford County, Pennsylvania

INTRODUCTION

Marcellus Shale is an organically rich black shale that is currently being explored through drilling as a prominent source of natural gas. The Marcellus Shale formation encompasses most of the sparsely populated Appalachian Basin, a physiographic province within the Appalachian Mountains comprised of sedimentary rocks that stretches from the Valley and Ridge Province in the east to the Appalachian Plateau in the west. Geographically it extends from Ontario, Canada through New York, Pennsylvania, Ohio, Maryland, West Virginia, Virginia, and a small portion of New Jersey (USGS 2013). Approximately one-third of the Marcellus Formation is situated in northern and western Pennsylvania and it covers over half of the state (Carter et

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al. 2011). The Marcellus Shale is considered to have the greatest economic potential out of all the gas-bearing shale formations in the United States (Gregory et al. 2011).

As discussed below, the rapid expansion of the gas industry throughout the Appalachian Basin has raised a variety of concerns and most of the focus to date has been on the potential environmental impacts on water resources. Few studies have addressed land use or land cover changes associated with this emerging industry and to our knowledge, this study represents one of the few to appear in the peer-reviewed literature (see Drohan et al. 2012 for another example). In this research, we focused on Bradford County, Pennsylvania because it is has the most permitted gas wells within Pennsylvania (Carter et al. 2011). We quantified land use and land cover changes associated with the construction of natural gas well pads, associated impoundment ponds, and access roads. We evaluated both the extent and types of change and we also quantified the variability of the number of wells per pad. We then used this information to estimate the extent and type of land use change in Bradford County if all wells permitted as of October 2011 were developed.

BACKGROUND ON MARCELLUS SHALE DRILLING

Shale gas is natural gas trapped in fractures and pore space in fine-grained shale. In order to viably extract the natural gas, a process called hydraulic fracturing is implemented at the drill sites. While hydraulic fracturing (or hydrofracking) has been practiced as a well stimulation technique since 1949, it was the innovation of horizontal drilling coupled with hydrofracking that enabled the modern natural gas boom in the Appalachian Basin. Hydraulic fracturing occurs when fluid containing water, sand, and up to 2% chemicals is pumped into the well at a high pressure. The pressurized fluid causes fractures in the shale, and the sand keeps the fractures open. This allows the natural gas to migrate into the well for extraction. By drilling through the shale horizontally, and thus exposing more of the shale for extraction, horizontal drilling increases the productivity of natural gas wells significantly. Horizontal drilling also allows for multiple wells to be sited within a single well pad, making it more economical than traditional vertical drilling, as well as more efficient by reducing land disturbance and creating greater access to the shale gas. The first producing shale gas well in Pennsylvania was a vertically drilled well completed by Range Resources Corporation in 2004 in Washington County. By mid-2011, the Pennsylvania Department of Environmental Protection (PADEP) had issued 6,488 well permits and 1,098 wells had been completed (Carter et al. 2011). Through August of 2013, an additional 6,336 permits were issued and 3,271 wells had been completed (PADEP 2013a).

The rapid expansion of the shale gas industry in Pennsylvania and throughout the Appalachian Basin has raised a number of social, economic, and environmental concerns, with environmental and related human health issues at the forefront. Water supply and water quality have received the most attention: most Marcellus wells generally use water as the fracking fluid and an average Marcellus frack job uses 2.9 million gallons of water (Carter et al. 2011). The water used in fracking contains a high concentration of salts, heavy metals, fracking chemicals, and other compounds, which is cause for concern as the potential for water supply contamination increases with increased water demands, spill potential, and the improper treatment of flowback water (Gregory et al. 2011).

Although 98% or more of the fracking fluid is comprised of water and sand, the chemical additives serve a variety of functions necessary in the process of hydraulic fracturing. For example, compounds such as methanol, formic acid, isopropanol, and acetaldehyde act as wintering agents, product stabilizers, and to prevent pipe corrosion. Gelling agents such as guar gum, ethylene glycol, polysaccharide blend, and petroleum distillate are used to hold the fractures open, allowing more gas to migrate into the well. Clay stabilizers such as choline chloride, sodium chloride, and tetramethyl ammonium chloride prevent swelling or shifting of the shale throughout the fracking process. Fracking fluid can also contain biocides, chemicals to prevent scale buildup within the pipes, acids to prevent the precipitation of metal oxides, and pH adjusting agents. Many chemicals are useful in multiple roles. For example, ethylene glycol is a non-emulsifier, gelling agent, and friction reducer (FracFocus 2013). From a human health perspective, the potential for surface water and groundwater contamination from fracking fluid is a cause for concern. A recent review of over 600 commonly used fracking chemicals showed that most (75%) could affect the skin, eyes, respiratory system, and gastrointestinal system; a significant portion also could affect the nervous, immune, and cardiovascular systems (40-50%) or act as endocrine disruptors (37%) (Colborn et al. 2011).

The Marcellus Shale has high concentrations of uranium and thorium. These radioactive isotopes are brought to the surface as the fracking water is extracted (flowback water). These low levels of radiation are usually not considered dangerous, but cannot be removed through water treatment. Wastewater from wells, which is temporarily stored on site in lined impoundment ponds, has been shown to contain radioactivity at levels higher than the level that federal regulators say is safe for water treatment plants to process (Urbina 2011).

Groundwater contamination from methane migration is another cause for concern. In Bradford County, Chesapeake Energy recently agreed to pay $1.6 million in damages to several families whose wells were contaminated, likely a result of methane migration from poorly cemented wells (Phillips 2012). Most of the documented cases of well water contamination due to drilling activities in Pennsylvania have been linked to gas wells that have not been properly sealed or that have been over-pressurized (Detrow 2013).

Additionally, condensate tanks and compressor stations that accompany well drilling activities emit a number of air pollutants, such as carbon disulfide, that have known negative impacts on human health (Schmidt 2011). The noise pollution that results from the extraction is also a cause for concern, as it can impact wildlife habitat and the aesthetic qualities of the environment (Johnson 2010, Price and Sprague 2012).

Because of these concerns, new state policies and regulations related to shale gas exploration and drilling have been developed. At the federal level, the Environmental Protection Agency has limited authority over shale gas development (Schmidt 2011), leaving the states to develop their own regulations. In Pennsylvania, the Department of Environmental Protection serves as the Commonwealth's regulatory agency for the oil and gas industry. The primary legislation that applies to the oil and gas industry is the Oil and Gas Act (Pennsylvania Act 223 of 1984), which requires operators to report drilling and production information and provides some protection for water resources and wetlands. More recently, the Commonwealth passed Pennsylvania Act 15 of 2010, which, among other things, requires disclosures for constituents of frack fluids. In addition, well construction standards and well integrity are specified to prevent casing failures, blowouts, fires or other impacts during the installation, completion (fracking), and operation (Carter et al. 2011; Pennsylvania Code, Chapter 78, Subchapter D, 78.71). As with other construction activities, the construction of well pads is subject to erosion and sediment control regulations. Much of the regulatory compliance issues are addressed through the permitting process, and PADEP also inspects well sites throughout the life cycle of the well (from construction to reclamation) (PADEP 2011a).

The most recent development has been the passage of impact fee legislation in early 2012. The new legislation allows counties or municipalities to enact a fee levied on gas producers within their boundaries. While

60% of fee revenues are returned to the county or municipality, the spending of the funds is limited to thirteen categories that focus on local resources potentially impacted by drilling activities, such as infrastructure maintenance, emergency preparedness, and affordable housing (PPUC 2013). The legislation also adds or extends minimum setback requirements between gas wells and existing buildings or water wells (increased from 200 feet to 500 feet), water extraction points (1,000 feet), and streams, wetlands, or water bodies (increased from 100 feet to 300 feet) (PADEP 2013b).

As highlighted by the above discussion, the primary focus of environmental discourse, scientific studies, and regulations has been on air and water quality impacts, coupled with the impacts on human health. Although the investigations of impacts of land use and land cover change and the accompanying physical, ecological, and aesthetic changes that can result from expanded gas drilling activities has been minimal, there are three notable exceptions. The Nature Conservancy (TNC) completed a study evaluating forest loss and fragmentation due to Marcellus drilling and its impacts on freshwater and rare species habitats in Pennsylvania (Johnson 2010). The study estimated that as of 2010, 1,416.4 hectares (3,500 acres) of Pennsylvania forest had been cleared for Marcellus gas development with an additional 3,439.8 hectares (8,500 acres) located within 91.4 meters (300 feet) of well pads, roads, and other infrastructure, thus highlighting the habitat impacts associated with forest fragmentation. The TNC study used aerial photos to assess current impacts and developed natural gas development projections. Potential future impacts were forecasted based on the number of drilling rigs in the area, the density of wells per pad, and an analysis of areas most likely to be targeted gas drilling.

Like the TNC study, Drohan et al. (2012) completed a statewide analysis of the landscape effects of drilling in Pennsylvania. They focused on the land cover changes due to well pad development with a specific emphasis on forest fragmentation and forest loss in headwaters. They also differentiate between well pad development on private lands and public lands. They found the majority of well pads occur in agricultural landscapes, but that a significant proportion (38%) occurs in forested areas; 23% of well pads have been located in core forest areas. Well pads have overwhelmingly been located on private lands, with only 10% occurring on public lands.

The U.S. Geological Survey (USGS) also completed a detailed study of land disturbance and land use change related to the natural gas extraction in Bradford and Washington counties in Pennsylvania, with a specific focus on investigating ecosystem impacts at landscape and watershed scales (Slonecker et al. 2012). Using aerial photos, Slonecker et al. (2012) documented changes associated with the development of well pads and road, pipelines, and impoundments. For Bradford County, they found 1,300.3 hectares (3,213.11 acres) of total land disturbance, 742.4 hectares (1,834.51 acres) of which was caused by well sites and roads and 1,226.4 hectares (3,030.5 acres) caused by impoundments. In terms of land cover change, they found that natural gas development had the greatest impacts on agricultural and forest lands, a pattern consistent with Drohan et al. 2012.

OBJECTIVES

Given the lack of systematic studies that focus on land use change related to Marcellus Shale drilling, the specific objectives of this research were to delineate all well pads associated with currently producing wells (as of October 2011) and accompanying impoundment ponds in Bradford County, along with new roads developed for access to the pads; determine how much land area has been changed as a result of the this infrastructure development; and determine what type of land cover was converted by the installation of the well pads. We also estimated the total potential amount and type of land cover change based on the current number of permitted wells as of October 2011, mean well pad size, road area, impoundment area, and mean number of wells per pad.

STUDY AREA: BRADFORD COUNTY, PENNSYLVANIA

In 2008, the Marcellus Shale gas industry reached Bradford County with 46 permits granted and 12 completed wells that year (Carter et al. 2011). Bradford County is located near the border between Pennsylvania and New York and encompasses 2971.75 km^2 (1,147.40 mi^2) (US Census Bureau 2010) (Fig. 1). It is largely agrarian with large tracts of forest intermixed (Bradford County, PA 2011a). Settlements are characterized by low-density development, with an overall population density of 54 people per square mile (US Census Bureau 2010). Since drilling began in 2008, the number of wells has increased rapidly (Bradford County, PA 2011b) (Fig. 2). The Pennsylvania Department of Environmental Protection (PADEP) reports that as of November 8, 2011, Bradford County, Pennsylvania has the highest number of permitted (more than 1,800) and actively drilled (more than 300) Marcellus Shale wells in the state. In fact, there are nearly three times as many permits issued and wells drilled in Bradford County than in any other county in Pennsylvania (PADEP 2011a). The formation is the deepest there, ranging from 75 feet to more than 250 feet of viable, gas-producing Marcellus Shale (PADCNR 2011).

DATA AND METHODS

Like the three studies discussed above (Johnson 2010, Drohan at al. 2012, and Slonecker et al. 2012), our study utilizes aerial photography and other remotely sensed data to characterize land use changes associated with Marcellus Shale drilling. We relied on a number of publicly available data sets to perform our analysis (Table 1). In order to delineate all currently developed well pads in Bradford County, we assumed any well pad containing producing wells as of October 2011(the date of the permit dataset used in this analysis) was a fully developed site (Fig. 3). We digitized the footprint of each well pad containing producing wells as observed in the 2010 aerial photos. By comparing the 2010 and 2005 air photos, we then identified roads that had been constructed for access to these pads. In addition, we identified new impoundment ponds (Fig. 4). This differs somewhat from the TNC and USGS studies, which also capture pipeline infrastructure. The USGS study also attempted to delineate all gas drilling activity – Marcellus and non-Marcellus, permitted and unpermitted sites, and sites at various stages of completion – while we relied on the PADEP database to identify permitted and producing sites only. Our research nevertheless serves as a good complement to existing studies, as it offers an additional perspective on the land use change impacts of Marcellus Shale drilling. Drohan et al. (2012) did not delineate well pads, but rather estimated pad locations based on the PADEP well permit database.

Once the delineation was complete, we calculated the total area of the infrastructure to establish the total amount of land change, then derived prior land cover types from the Chesapeake Bay Land Cover Dataset (CBLCD) 2006 dataset (Irani and Claggett 2011) within the developed well pad footprints (Fig. 4). We note that Bradford County did not have any producing or permitted wells until 2008, so no land use changes related to the Marcellus Shale industry would have occurred prior to this time.

We calculated the land cover area tabulations using the well pad digitized polygons overlaid by the CBLCD 2006 land cover data. If the polygon intersected the centroid of a land cover pixel, we included the pixel in the tabulations. If the centroid was outside of the polygon, we did not include the pixel.

To forecast the potential future land loss and land cover change due to Marcellus Shale gas extraction, we assumed that all permitted wells would eventually go into production and that the impacts on the type of land

Figure 1. Location of Bradford County within Pennsylvania (upper map) and location of permitted well sites as of October 2011 within Bradford County (lower map).

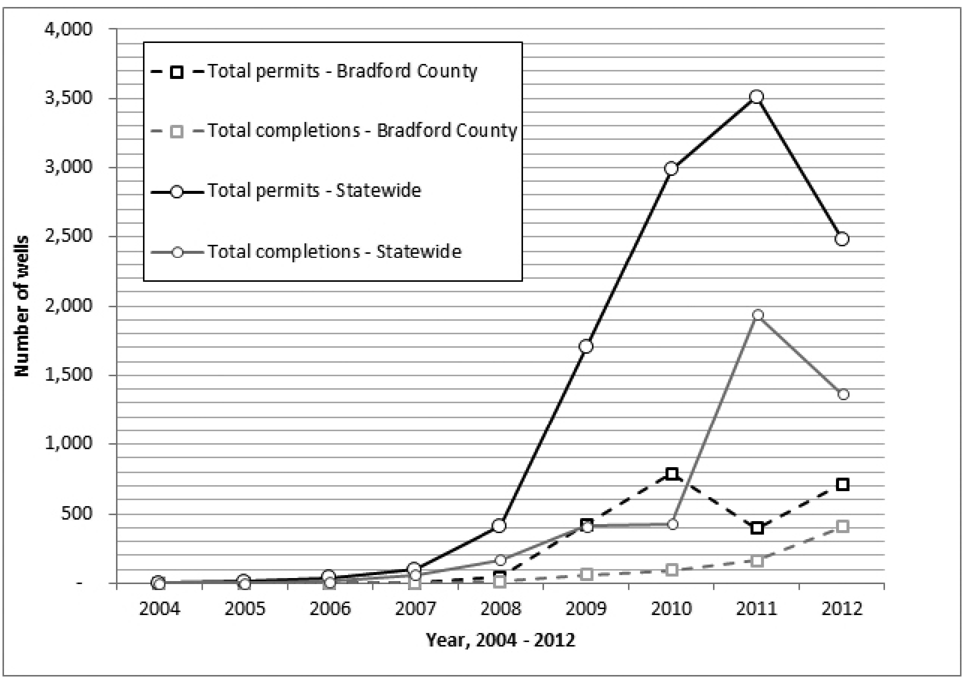

Figure 2. Well permits and completions for Bradford County and the Commonwealth of Pennsylvania, 2004 – December 2012 (Carter et al. 2011 and PDEP 2013a).

Table 1. Data sets used in analysis

Data set	Description	Source
Bradford County boundary	The Pennsylvania County Boundaries layer shows all 67 county boundaries in Pennsylvania. The Bradford County boundaries represented in this layer were used to delineate our study area.	Pennsylvania Department of Transportation. 2010. Bureau of Planning and Research, Cartographic Information Division. PennDOT - Pennsylvania County Boundaries. Harrisburg, PA: Pennsylvania Department of Transportation. Available from Pennsylvania Spatial Data Access website (PASDA), www.pasda.psu.edu.
Permitted Marcellus Shale wells as of October 2011	Permitted Marcellus Shale wells were derived from PA DEP's Oil & Gas Locations data set. The oil and gas location layer shows individual points for all permitted locations for oil and gas mining activities in Pennsylvania. We subsetted the points that represent permitted Marcellus Shale drilling locations in Bradford County.	Pennsylvania Department of Environmental Protection. 2011. Oil & Gas Locations. Harrisburg, PA: Pennsylvania Department of Environmental Protection. Available from Pennsylvania Spatial Data Access website (PASDA), www.pasda.psu.edu.
Producing Marcellus Shale wells as of October 11, 2011	ESRI's on-line database provided a display-only geographic layer, derived from the PA DEP's Permitted Marcellus Shale wells, that represented all permitted Marcellus Shale wells that are currently producing. We used this layer to identify wells in the permitted Marcellus Shale layer that were actively producing gas.	Producing Gas Wells – Pennsylvania. Last modified October 12m 2011. Available from the ESRI on-line database http://www.arcgis.com/home/item.html?id=64fb67f22688416581dbff357 23c6cee
2005 aerial photos	The National Agricultural Imagery Program (NAIP) provides a tiled data set of aerial photos for 2005 at a resolution of $4m^2$.	U.S. Department of Agriculture. 2005. USDA - NAIP County Mosaics for Pennsylvania, 2005. Salt Lake City, Utah: USDA_FSA_APFO Aerial Photography Field Office. Available from Pennsylvania Spatial Data Access website (PASDA), www.pasda.psu.edu.
2010 aerial photos	NAIP provides a tiled data set of aerial photos for 2010 at a resolution of $1m^2$.	U.S. Department of Agriculture Farm Service Administration. 2010. Aerial Photography Field Office. NAIP Digital Ortho Photo Image, 2010. Salt Lake City, Utah: USDA FSA Aerial Photography Field Office. Available from Pennsylvania Spatial Data Access website (PASDA), www.pasda.psu.edu.
Chesapeake Bay Watershed Land Cover Data (CBLCD) for 2006	The USGS funded the production of the CBLCD representing four dates: 1984, 1992, 2001, and 2006. These data were derived from Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper satellite imagery. Each of the four datasets consists of 16 land use and land cover classes, are temporally comparable, and encompass the entire Chesapeake Bay Watershed and intersecting counties. We subsetted the 2006 data set for Bradford County.	Irani, F.M. and P. Claggett. 2010. Chesapeake Bay Watershed Land Cover Data Series. U.S. Geological Survey Data Series 2010-505. ftp://ftp.chesapeakebay.net/Gis/CBLCD_Series/

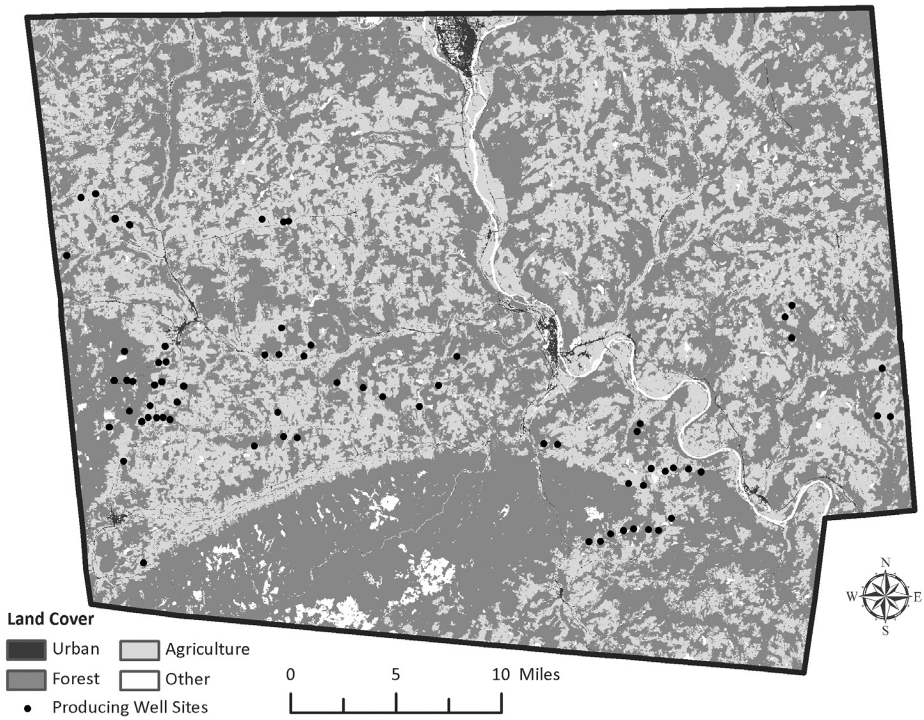

Figure 3. Producing well sites as of October 2011 with the 2006 CBLCD in the background.

cover change would remain proportionally consistent with our current findings. However, similar to Johnson (2010), we generated a range of land cover change forecasts from high to low based on the observed variability of well clustering and well pad size.

In order to quantify the mean number and range of wells per pad, we attached a unique well pad identification number to each permitted well point (producing and non-producing wells) within developed well pads. This allowed us to summarize the total number of points by well pad and then generate descriptive statistics, including the maximum, minimum, mean, and standard deviation, for the number of wells per pad. We determined the total number of permitted wells (1,565) by subtracting the number of producing and non-producing Marcellus Shale wells in Bradford County that are already located on a developed pad (322) from the total number of permitted wells in the County (1,887).

We then generated estimates of land area developed based on the mean number of wells per pad, the mean pad size, and the mean area of additional infrastructure per pad. To estimate the upper and lower bounds of possible land change, we also calculated high and low estimates in terms of the number of pads generated – we used 1 SD below and above the mean number of wells per pad – and high and low estimates in terms of pad size (1 SD above and below the mean pad size). In terms of additional infrastructure, we used only the mean area per pad to simplify the analysis. This is a reasonable assumption, since most variability in potential land use change is associated with well pad size and the number of wells per pad. This approach generated nine total scenarios that capture a range of possible scenarios in terms of well pad size and number of new well pads. We note that these scenarios are based on the

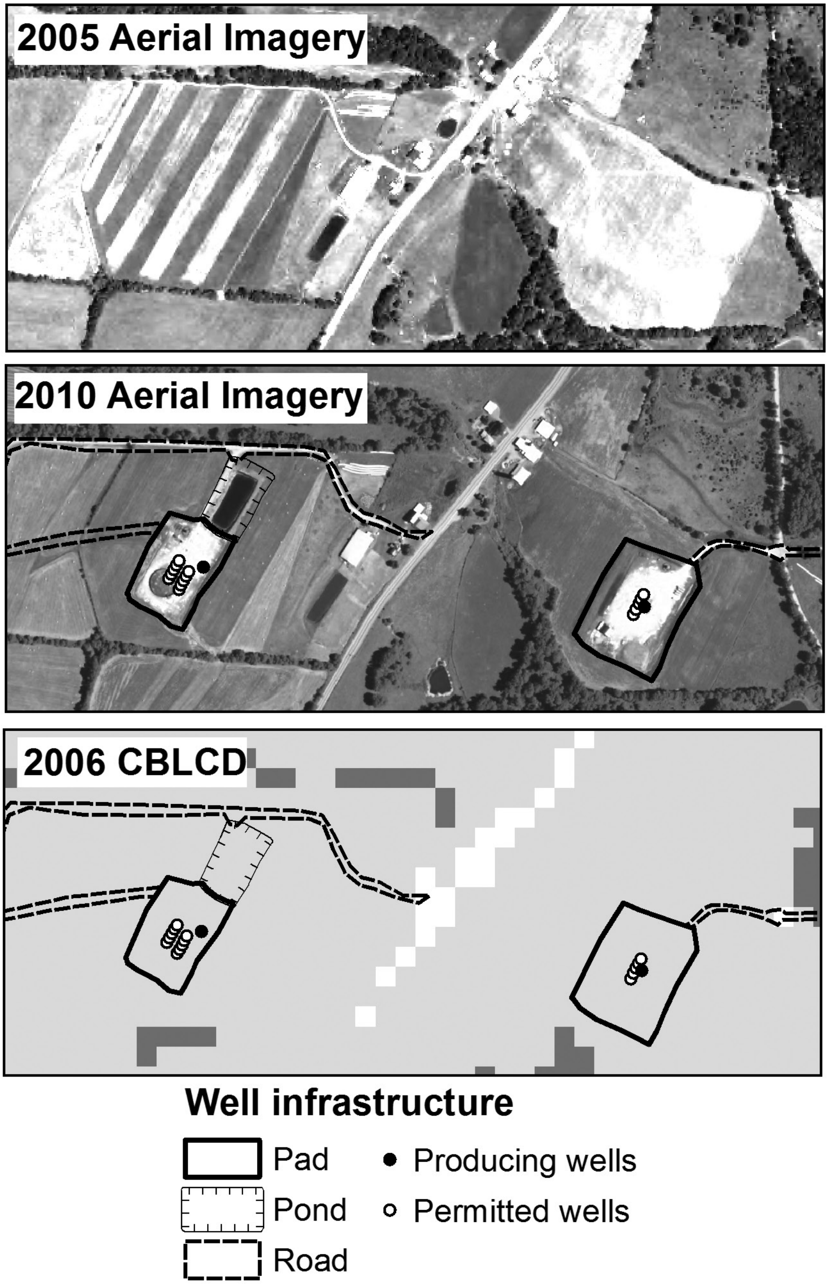

Figure 4. The upper image shows an example of the 2005 aerial imager, the middle image shows 2010 imagery with digitized well pads, access roads, and a retention pond, and the lower image shows the well infrastructure overlaid on the 2006 CBLCD dataset (white is developed land, light gray is agriculture, dark gray is forest).

distribution of wells per pad and well pad size that existed in October 2011, but that by using +/- 1 SD we are capturing a reasonable level of variability that is not influenced by extreme values in our dataset.

For each scenario, we calculated the forecasted number of well pads by dividing the number of undeveloped, permitted wells (1,565) by the expected number of wells per pad, and multiplied the result by the expected pad area. This resulted in scenarios ranging between 2.02 and 7.32 wells per pad and well pads ranging in size from 1.34 to 3.58 hectares. Finally, we added the mean area of new infrastructure (roads and impoundment ponds) expected to accompany each pad. To estimate the type of land changes under each scenario, we allocated the total change proportionally across land cover types based on changes that have resulted from current development. Although we know the geographic locations of the permit sites, we were not able to estimate land use changes directly since the number of wells per pad, well pad design, and location of access roads are not known.

RESULTS

As of October 2011, we estimate that a total of 276.84 hectares (684.09 acres) of land have been converted to 69 well pads and associated infrastructure (Table 2). The mean well pad size is 2.45 hectares (6.07 acres) with a standard deviation of 1.12 hectares (2.76 acres). Each well pad requires, on average, an additional 1.56 hectares (3.85 acres) of additional infrastructure (road area and impoundment pond area). Agricultural land has been the most heavily impacted, capturing 185.58 hectares (458.58 acres or 67%) of the land change, followed by forests, which represent 80.28 hectares (198.38 acres or 29%) of the observed changes (Table 3). This acreage is inclusive of the well pad, access roads, and impoundment ponds, but does not include pipelines.

As of October 2011, the number of wells in production totaled 169, with an additional 153 permitted wells located on developed pad sites. As depicted in Fig. 4, there are often multiple wells per well pad site, with some in production and some permitted but not in production. Through analysis of all developed well pad sites, it was determined that the mean of permitted wells (not necessarily in production) per well pad was 4.67 with a standard deviation of 2.65 (Table 4).

As of October 2011, there have been 1,887 permits in Bradford County issued to energy companies. These permits allow for the companies to drill, assuming that the land has been leased or bought from the current land owners. There are 322 permitted wells within the developed well pads, with 169 of them currently in production. Assuming the 1,565 remaining permitted wells are developed on new pads, we estimate that between 214 and 334 additional well pads will be constructed, resulting in a total amount of land change of between 620.60 hectares (1,533.53 acres) and 3,983.50 hectares (9,843.43 acres). If the development follows the observed averages, in terms of the mean number of wells per pad, the mean well pad size, and the mean additional infrastructure area we estimate 1,346.70 hectares (3,327.76 acres) to be converted from their current use to a well pad (Table 5).

Because we estimated the type of potential land change based on observed impacts, agriculture is expected to see the largest changes, with 902.75 hectares (2,230.77 acres) being converted, with a range of 416.02 – 2,670.34 hectares under the lowest and highest scenarios. Forests could experience a loss of 390.56 hectares (965.02 acres) under the mean scenario, with a range of 179.97 – 1,155.16 hectares under the lowest and highest scenarios (Fig. 5).

DISCUSSION AND CONCLUSIONS

In Bradford County, the 69 well pads and associated infrastructure that had been developed as of October 2011 were found to total 276.84 hectares (684.09 acres). This is less than one percent of the total acre-

Table 2. Summary statistics in hectares (and acres) for well infrastructure.

	Well pads (N=69)	Holding ponds (N=13)	Access roads (N=60)	Total infrastructure
Total area	169.56 (418.99)	34.2 (84.51)	73.08 (180.58)	276.84 (684.09)
Mean	2.46 (6.07)	5.13 (12.68)	1.22 (3.01)	1.95 (4.82)
Range	0.54-7.74 (1.33-19.13)	0.63-5.13 (1.56-12.68)	0.02-6.84 (0.05-16.90)	0.02-7.74 (0.05-19.13)
Standard deviation	1.12 (2.76)	1.48 (3.65)	1.82 (4.51)	1.61 (3.97)

Table 3: Area in hectares (acres) and types of land converted to well infrastructure.

Well pads (N = 69)	**Area converted**	**Proportion of total**
Forest	40.50 (100.08)	0.15
Shrub/Scrub	4.59 (11.34)	0.02
Grassland	1.17 (2.89)	0.00
Agriculture	122.31 (302.23)	0.44
Other	0.99 (2.45)	0.00
Total	169.56 (418.99)	0.61
Holding ponds (N=13)		
Forest	6.30 (15.57)	0.02
Shrub/Scrub	1.98 (4.89)	0.01
Grassland	0.45 (1.11)	0.00
Agriculture	25.47 (62.94)	0.09
Other	0.00 (0.00)	0.00
Total	34.20 (84.51)	0.12
Access roads (N=60)		
Forest	33.48 (82.73)	0.12
Shrub/Scrub	1.53 (3.78)	0.01
Grassland	0.18 (0.44)	0.00
Agriculture	37.80 (93.41)	0.14
Other	0.09 (0.22)	0.00
Total	73.08 (180.58)	0.26
All infrastructure		
Forest	80.28 (198.38)	0.29
Shrub/Scrub	8.10 (20.02)	0.03
Grassland	1.80 (4.45)	0.01
Agriculture	185.58 (458.58)	0.67
Other	1.08 (2.67)	0.00
Total	276.84 (684.09)	1.00

Table 4. Summary statistics for all wells (producing (n = 169) and non-producing (n = 153, total n = 322) contained in well pads that have wells currently in production (n = 69) as of October 2011. (Data source DEP 2011)

Statistic	Number of wells
Minimum	1
Maximum	13
Sum	322
Mean	4.67
Standard deviation	2.65

Table 5. Total forecasted number of well pads and associated land change in hectares (acres) under each scenario, assuming the placement of an additional 1,565 wells.

	Mean wells per pad (335 pads at 4.67 wells per pad)	Higher well clustering (+1 SD above the mean) (214 pads at 7.32 wells per pad)	Lower well clustering (-1 SD below the mean) (775 pads at 2.02 wells per pad)
Mean well pad size (2.46 hectares) + 1.56 hectares of additional infrastructure	1,346.70 (3,327.76)	860.28 (2,125.79)	3,115.50 (7,698.56)
Compact well pads (1 SD below the mean, 1.34 hectares) + 1.56 hectares of additional infrastructure	971.50 (2,400.63)	620.60 (1,533.53)	2,247.50 (5,553.68)
Large well pads (1 SD above the mean, 3.58 hectares) + 1.56 hectares of additional infrastructure	1,721.90 (4,254.90)	1,099.96 (2,718.06)	3,983.50 (9,843.43)

age for Bradford County. The USGS study reports 617.7 hectares of all Marcellus sites and roads (Slonecker et al. 2012), so the data set on which we relied, of producing wells, is underestimating the total impact of drilling activities on land use changes in Bradford County. Furthermore, in the TNC study, Johnson (2010) found that on a per pad basis a mean of 2.3 hectares (5.7 acres) would be cleared for associated infrastructure, while our estimate was 1.56 hectares per pad. The TNC study, however, included pipelines while ours did not, therefore our estimates do not capture the total picture of land use change impacts.

Acknowledging the conservative nature of our estimates, Johnson (2010), Drohan et al. (2012), and Slonecker et al. (2012) note that the land conversion process comprises only part of the total impact shale gas drilling is having on the landscape. Forest fragmentation and loss of interior forest habitat are commensurate with the changes described in all three studies. Based on their analysis in Bradford and Washington counties, Slonecker et al. (2012) estimate that interior forest loss is approximately double that of the total forest loss and the increase in forest edge increases at the same rate of forest loss and, as noted previously, Drohan et al. (2012) found a significant impact on core forest areas.

It is worthwhile to compare our findings in terms of well pad development and the number of wells per pad with those of prior

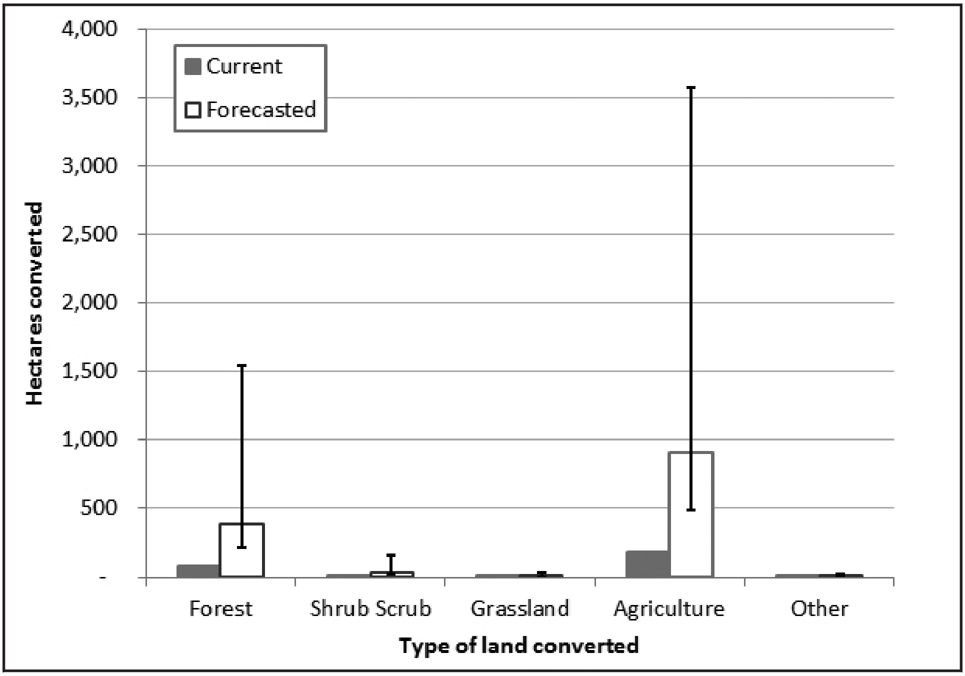

Figure 5. Current and forecasted land change due to well pad development by land cover type, in acres. The bars on the forecasted data indicate the upper and lower estimates across the nine forecast scenarios.

studies. We found the mean well pad size to be 2.46 hectares (6.07 acres), although there is relatively high variability as reflected in the standard deviation (1.12 hectares, 2.76 acres). In the statewide TNC study, Johnson (2010) found the mean well pad size to be 1.25 hectares (3.1 acres) but did not report the standard deviation. These differences could be due to a number of reasons. A different method in characterizing the edges of well pads is likely one contributing factor. However, it may also represent a shift in the maturing gas industry towards greater consolidation of wells and drilling infrastructure. In terms of the number of wells per pad, the TNC study reports a mean of 2 *producing* wells per pad (Johnson 2010), while Drohan et al. (2012) report that more than 75% of pads have only 1 or 2 wells per pad. We found a slightly higher mean of 2.45 *producing* wells per pad (SD = 1.45 wells per pad) and 4.67 *producing and permitted* wells per pad (SD = 2.64 wells per pad). Since Bradford County came later into the shale boom, it likely exhibits more recent patterns of development that have greater consolidation of infrastructure. Indeed, Johnson (2010) notes that this is a likely trend for the gas industry, since greater consolidation of infrastructure is more economical and efficient, and Drohan et al. (2012) found that the mean and maximum number of wells per pad was increasing every year.

Examining the type of land cover converted to well pads reflected a strong trend: agricultural land was the most converted land cover type, with about 186 hectares (459 acres) (67% of total change) having been converted as of the 2010 aerial imagery. Forest land cover was the second most highly converted, with just over 80 hectares (198 acres) (29% or total change) having been converted. Based on total land cover amounts for the entire county, forested land cover comprises more than fifty percent of Bradford County, yet it is converted only about 29% of the time, versus agriculture which is nearly 67%. These findings are consistent with Johnson (2010), Drohan et al. (2012) and Slonecker et al. (2012), indicating a clear preference for agricultural land. Gas companies likely prefer to secure land for well development in agricultural areas as a way to lower costs associated with well pad development. It is less expensive and less invasive to clear agricultural land for development. In addition, gas companies are required to do restoration and reclamation on the land post-drilling, and agricultural land is the most cost-efficient to restore.

In terms of potential future change in Bradford County given the number of permits issued as of November 2011, our scenarios indicate total land change ranging from 620.60 hectares (1,533.53 acres) to 3,983.50 hectares (9,843.43 acres). Within this large range, we can speculate on what is more likely in terms of current and future development. For example, due to economic pressures, it is not likely that drilling companies would move toward a scenario where there are fewer wells per pad, as reflected in our low well clustering estimate of 2.02 wells per pad, making the mean number of wells per pad (4.67) or higher well clustering (7.32 wells per pad) more reasonable. Johnson (2010) notes that there can be up to 10 wells per pad but due to irregularly shaped leases, topography, and other factors, this level of well density is rare. Similar reasoning applies to well pad construction. Therefore, a more reasonable range to consider in terms of land change impacts of well pads given the current number of leases would be 620.60 hectares (1,533.53 acres) to 1,346.70 hectares (3,327.76 acres). Again, we emphasize that our estimates do not include all associated infrastructure. We anticipate that most of these changes would occur on agricultural land, although land use change processes could be complex. For example, if royalties received by farmers are sufficient to replace their farm income, farmland abandonment coupled with drilling activity may become a more prominent trend. Likewise, impacts are likely to be complex. For example, changes in hydrology may occur as the continued development of well pad sites increases impervious surface cover.

Implications of current and future changes due to drilling activity on agricultural and forested landscapes are a cause for concern. A number of farmers in Bradford County adhere to no-till farming, and have worked many years with soil conservation techniques (PADEP 2004). Excavation for the pipelines and wells disturbs the soil, and often new topsoil is imported, leaving the land with a different soil composition. Most pipelines are installed in the dry months so as to alleviate excess storm water runoff from bare and exposed soil (Madden and Sheppard 2011). However, farmers have the potential to see soil compaction in their fields from repeated truck and equipment traffic along the access roads and pipelines. The soil compaction can have long term effects for farmers and crop production, as biological processes change with the structural change in the soil. Subsoil compaction in particular has long-term adverse effects and can cause severe environmental degradation. The subsoil compaction causes prolonged periods of surface soil saturation and conversely surface runoff and erosion (Duiker and Micsky 2009).

Another consideration is the fragmentation of forested land by not only the installation of well pads but also the installation of pipelines and access roads. This fragmentation could lead to decreased wildlife habitat, decreased diversity, and an increase in non-native species, as gas companies run the risk of introducing invasive species during the reclamation process (Rodgers et al. 2008). Johnson (2010) also emphasizes the potential of expanded edge effects on interior forest habitat, negative impacts on freshwater aquatic habitats and rare species, and a decrease in the quality of outdoor recreation amenities.

This latter point touches on the potential for aesthetic impacts and impacts on recreational resources that are important economic resources for Bradford County and many of the counties in the northern tier of Pennsylvania. Bradford County boasts that it is the "heart of the Endless Mountain Region in northeastern Pennsylvania" (Bradford County, PA 2012a) and visitor guides to this region emphasize the quality of its natural scenery, opportunities to sample locally produced foods and crafts, and a variety of outdoor recreational activities that include hunting, fishing, skiing, canoeing, and kayaking (Endless Mountains Visitors Bureau 2012, Endless Mountains Heritage Region 2009). While Pennsylvania has one of the largest networks of public lands in the eastern United States (4.5 million acres), subsurface mineral development is permissible on the vast majority of this land. Johnson (2010) reports that mineral rights have already been leased under 2.2 million publicly owned lands in Pennsylvania.

We note that the impacts from Marcellus Shale gas drilling go far beyond just Bradford County. Forest fragmentation, drilling adjacent to waterways and water removal from the Susquehanna River and tributaries could affect the health of Pennsylvania waterways and ultimately the Chesapeake Bay, which is the focus of a multi-state and federal restoration effort (CBP 2013). These forests are responsible for absorbing pollutants, stabilizing soil, and buffering waterways from surface runoff. Large scale forest removal could have profound impacts for Pennsylvania in reaching its required pollutant reductions for discharge into the Chesapeake Bay. About 46% of Marcellus Shale gas drilling is projected to take place within the Chesapeake Bay watershed. Increasing the amount of bare soil could increase nitrogen loads by 30,000 – 80,000 pound/year, phosphorous loading could increase 15,000 – 40,000 pound per year, and sediments could increase by 18 – 45 million pounds per year. (Blankenship 2011, Johnson 2010). Drohan et al. (2012) found that the Susquehanna River Basin, which provides over two-thirds of the freshwater to the Chesapeake Bay (Horton 2003), has 60% of existing pads in Pennsylvania, and 54% of permitted pads.

There are opportunities for mitigation even as the gas industry expands. For example, the Pennsylvania Department of Environmental Protection urges the use of riparian buffer zones (particularly forested riparian buffer zones) and has prohibited the removal of them for extraction purposes (Title 25 Chapter 102, The Pennsylvania Code). PADEP also requires the use of best management practices for erosion and sediment control for drilling sites under 5 acres, while a more structured permit is required for drilling sites that exceed 5 acres (PADEP 2011b). However, because of the increased intensity of well pad development, these codes and permitting regulations are being reviewed in order to determine if they appropriately protect waterways in accordance with The Clean Streams Law (PADEP 2011b).

In the TNC study, Johnson (2010) points out that impacts can be further mitigated by smarter placement of well pads, an option that is supported by horizontal drilling technology (although not necessarily by patterns of landownership and lease holdings). Assuming a "modest shift" (p. 26) in well pad locations to reduce the impacts on forest, total forest loss could be reduced by as much as 40%. Drohan et al. (2012) echo this sentiment, noting that because most current development is on private land, "an organized approach to siting drilling infrastructure could help minimize the development on forest lands and potential damage to waterways, and help manage development on agricultural land" (p. 1073).

In conclusion, our study highlights one aspect of the current and potential land use changes that accompany drilling in the Marcellus Shale, that of well pad and road construction. As pointed out, other infrastructure will accompany each well pad and commercial and residential development has increased in order to sustain the population influx and meet the growing need for housing and community amenities (Pupovac 2012). This development and land conversion was not examined in this research. Our estimates, especially those regarding observed changes through October 2011, should be considered conservative. While our study provides a quantitative basis for understanding some impacts of land use change impacts related to the natural gas industry, future studies are still needed in order to provide decision makers, especially at the state and local level, with the information they need to respond to the rapidly changing circumstances associated with the current gas boom.

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