# Damascus Citizens for Suistainability

Continuing from part one of our comment on material delivered to the DRBC at its September, 2013 meeting. THIS IS PART 2 OF 2

I am asking the DRBC to note the material from DCS's September, 2013 presentation to the DRBC at this link: https://www.dropbox.com/sh/85sf163ufql57iy/AABklVH2yH3kVoHl9xDsBGdza?dl=0

Attached is the outline of exemptions, 'loopholes' fought for and held by the industry to avoid liability for damages they knew they would cause.

Also attached are USGS papers on landscape damage, including fragmentation and more, in counties with extensive drilling in PA.

Transcript of Al Appleton, former NYC DEP commissioner at that DRBC meeting is also attached as are two papers (combined to one file) on aquifer water damage from gas migration by Jackson at Duke and a paper on Silica during hydraulic fracturing that are relevant.

This is part 2 of 2 on material delivered to the DRBC at its September, 2013 meeting.

# LOOPHOLES FOR POLLUTERS –
## The oil and gas industry's exemptions to major environmental laws

**Loopholes:** The oil and gas industry is exempt from key provisions of seven major federal environmental laws — allowing practices that would otherwise be illegal. Some exemptions date back decades. Others were adopted as recently as 2005.

While states and tribes have tried to fill the gaps with their own rules and regulations, they vary widely in effectiveness and enforcement. Federal laws provide consistent standards that equally protect all Americans. That's why it's essential to reverse these federal loopholes.

### 1. The Safe Drinking Water Act – SDWA

The Safe Drinking Water Act[1] (SDWA) of 1974 was established to protect America's drinking water. It covers waters actually or potentially designated for drinking, whether from above ground or underground sources.

The Energy Policy Act of 2005 exempted hydraulic fracturing (fracking) from SDWA[2] oversight, leaving drinking water sources in the 34 oil and gas producing unprotected from the host of toxic chemicals used during fracking. Congress qualified this exemption to regulate diesel fuel additives used during fracking, which requires industry to apply for a SDWA permit if they are using diesel fuel to hydraulically fracture a well.

### 2. The Clean Air Act – CAA

The Clean Air Act[3] (CAA), adopted in 1970, is the comprehensive federal law that regulates air emissions from area, stationary, and mobile pollution sources. The CAA established limits for major pollution sources called the National Emission Standards for Hazardous Air Pollutants (NEHAPS)[4]. NEHAPS must be met by installing the Maximum Achievable Control Technology (MACT) for each source.

Smaller sources of pollutants that are under common control by a single operator, are located in close proximity to each other, and perform similar functions are considered as one source of emissions. This aggregation allows for the CAA oversight of smaller sources that, when concentrated, may actually be as harmful as larger sources.

Unfortunately, the CAA exempts oil and gas wells, and in some instances pipeline compressors and pump stations, from aggregation. This exemption to the aggregation requirement allows the oil and gas industry—which often operates many small facilities in one area—to pollute the air while being largely unregulated under the CAA.

In addition, in 1991 hydrogen sulfide was removed from the list of Hazardous Air Pollutants under the CAA. This elimination has remained despite a 1993 EPA study, *Hydrogen Sulfide Air Emissions Associated with the Extraction of Oil and Natural Gas,* which clearly concludes that accidental releases of hydrogen sulfide during oil and gas development are a serious air quality concern and pose a great risk to public health. Common symptoms of exposure to low levels of hydrogen sulfide can include headache, skin complications, respiratory problems and system damage, confusion, verbal impairment, and memory loss.

### 3. Clean Water Act – CWA

Enacted in 1972 , the Federal Water Pollution Control Act[5], commonly known as the Clean Water Act (CWA), establishes the basic structure for regulating discharges of pollutants into the waters of the United States.

In 1987, Congress amended the CWA to require EPA to develop a permitting program for stormwater runoff — but exempted oil and gas production[6].

The 2005 Energy Policy Act amended the CWA to redefine sediment as a nonpollutant. This redefinition broadened the existing exemption for stormwater discharges to oil and gas construction. These exemptions leave streams and rivers in high oil and gas areas unprotected from sediment run-off caused by the construction and operation of well pads, pipelines, drill rigs,

**The oil and gas industry is exempt from key provisions of seven major federal environmental laws — allowing practices that would otherwise be illegal.**

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# LOOPHOLES FOR POLLUTERS –

## The oil and gas industry’s exemptions to major environmental laws

### 4. Resource Conservation and Recovery Act – RCRA

Adopted in 1976, the Resource Conservation and Recovery Act[7] (RCRA) is the principal federal law that governs the disposal of solid and hazardous wastes. The law takes a “cradle to grave” approach to ensure that wastes are handled properly from the point of creation to transport to disposal.

In 1980, Congress exempted oil field wastes (which includes waste from natural gas production) from RCRA[8] until EPA proved they were a danger to human health and the environment. Rather than do so, EPA eventually ceded authority to regulate these wastes to the states.

This exemption leaves produced water, drilling fluids, and hydraulic fracturing fluids from oil and gas production unregulated under the nation’s premier hazardous waste law. This allows unsafe handling of toxic substances, including their conventional transport on roads and treatment in municipal rather than specialized facilities.

### 5. Comprehensive Environmental Response, Compensation, and Liability Act – CERCLA

Commonly known as the “Superfund” law, the Comprehensive Environmental Response, Compensation, and Liability Act[9] (CERCLA) of 1980 makes liable those responsible for a spill or release of a hazardous substance into the environment.

Included in the list of hazardous substances under CERCLA are benzene, toluene, ethylbenzene, and xylene (Btex)– chemicals found in crude oil and petroleum.

Yet CERCLA exempts these substances from liability requirements if they are found in crude oil and petroleum[10] (which are used in natural gas production). Thus, hazardous chemicals that would otherwise be regulated under CERCLA are immune from the statute. The definition of hazardous substance also excludes natural gas, natural gas liquids, liquefied natural gas, and synthetic gas usable for fuel.

In addition, Superfund allows “Potentially Responsible Parties” to be held liable for clean-up costs for a release or threatened release of a “hazardous substance.” But CERCLA defines this term to exclude oil and natural gas. Consequently, industry has little incentive to clean up its hazardous waste, or to minimize leaks and spills, in part because the exemption allows companies to escape liability when these problems occur.

### 6. National Environmental Policy Act – NEPA

The National Environmental Policy Act[11] (NEPA) of 1970 establishes the broad national framework for protecting our environment. NEPA’s ensures the federal government gives proper consideration to the environment before undertaking any major federal action (including involvement in industrial projects) that significantly affects the environment.

The Energy Policy Act of 2005 stripped NEPA’s strong requirements for public involvement and environmental review when it comes to several oil and gas related activities[12]. It stipulated that they should be analyzed and processed by the Interior and Agricultural Departments under a much narrower and weaker process known as a “categorical exclusion[13]” (CE), as opposed to the more comprehensive and stringent Environmental Assessment[14] (EA) or Environmental Impact Statement[15] (EIS) required under NEPA. In addition, a CE does not allow for any public comment. In 2006 and 2007, the BLM granted this exemption to about 25 percent of all oil and gas wells approved on public land[16] in the West.

### 7. The Toxic Release Inventory of EPCRA

The Toxic Release Inventory[17] (TRI) was created by section 313 of the Emergency Planning and Community Right-to-Know Act[18] (EPCRA) of 1986. It requires most industries to report significant of toxic substances to the EPA, which then aggregates and disseminates the information to the public.

The information on chemical use and release includes point and fugitive onsite air releases, water releases, on and off-site land releases, underground injection, transfers to a Publicly Owned Treatment Works (POTW) or waste management facility (including the name and address of the facility), and the use of specific on-site waste treatment and management practices.

But despite their use of toxic chemicals throughout production, oil and gas facilities are not required to report to the TRI[19]. This exemption leaves communities in oil and gas producing areas in the dark about what chemicals are being released—making it difficult to attribute responsibility and seek remedy for resulting health and environmental problems.

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### Sources

1 http://water.epa.gov/lawsregs/rulesregs/sdwa/index.cfm
2 http://halliburton.earthworksaction.org/
3 http://www.epa.gov/air/caa/
4 http://cfpub.epa.gov/compliance/resources/policies/civil/caa/details.cfm?CAT_ID=&SUB_ID=92&templatePage=7&title=National%20Emissions%20Standards%20for%20Hazardous%20Air%20Pollutants%20(NESHAPs)
5 http://cfpub.epa.gov/npdes/cwa.cfm?program_id=45
6 http://ncseonline.org/nle/crsreports/10Sep/97-290.pdf
7 http://www.epa.gov/epawaste/inforesources/online/index.htm
8 http://www.epa.gov/osw/nonhaz/industrial/special/oil/oil-gas.pdf
9 http://www.epa.gov/superfund/policy/cercla.htm
10 http://www.epa.gov/superfund/policy/release/rq/index.htm#substance
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13 http://en.wikipedia.org/wiki/National_Environmental_Policy_Act#CE_.28Categorical_Exclusion.29
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19 http://www.epa.gov/tri/lawsandregs/naic/ncodes.htm

NOTE: this fact sheet is a synopsis of a more comprehensive white paper available at http://oilgas-exemptions.earthworksaction.org

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# Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction

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**Horizontal drilling and hydraulic fracturing are transforming energy production, but their potential environmental effects remain controversial. We analyzed 141 drinking water wells across the Appalachian Plateaus physiographic province of northeastern Pennsylvania, examining natural gas concentrations and isotopic signatures with proximity to shale gas wells. Methane was detected in 82% of drinking water samples, with average concentrations six times higher for homes <1 km from natural gas wells ($P = 0.0006$). Ethane was 23 times higher in homes <1 km from gas wells ($P = 0.0013$); propane was detected in 10 water wells, all within approximately 1 km distance ($P = 0.01$). Of three factors previously proposed to influence gas concentrations in shallow groundwater (distances to gas wells, valley bottoms, and the Appalachian Structural Front, a proxy for tectonic deformation), distance to gas wells was highly significant for methane concentrations ($P = 0.007$; multiple regression), whereas distances to valley bottoms and the Appalachian Structural Front were not significant ($P = 0.27$ and $P = 0.11$, respectively). Distance to gas wells was also the most significant factor for Pearson and Spearman correlation analyses ($P < 0.01$). For ethane concentrations, distance to gas wells was the only statistically significant factor ($P < 0.005$). Isotopic signatures ($\delta^{13}C\text{-}CH_4$, $\delta^{13}C\text{-}C_2H_6$, and $\delta^{2}H\text{-}CH_4$), hydrocarbon ratios (methane to ethane and propane), and the ratio of the noble gas $^4He$ to $CH_4$ in groundwater were characteristic of a thermally postmature Marcellus-like source in some cases. Overall, our data suggest that some homeowners living <1 km from gas wells have drinking water contaminated with stray gases.**

carbon, hydrogen, and helium isotopes | groundwater contamination | geochemical fingerprinting | fracking | hydrology and ecology

Unconventional sources of gas and oil are transforming energy supplies in the United States (1, 2). Horizontal drilling and hydraulic fracturing are driving this transformation, with shale gas and other unconventional sources now yielding more than one-half of all US natural gas supply. In January of 2013, for instance, the daily production of methane ($CH_4$) in the United States rose to ~$2 \times 10^9$ $m^3$, up 30% from the beginning of 2005 (3).

Along with the benefits of rising shale gas extraction, public concerns about the environmental consequences of hydraulic fracturing and horizontal drilling are also growing (4, 5). These concerns include changes in air quality (6), human health effects for workers and people living near well pads (5), induced seismicity (7), and controversy over the greenhouse gas balance (8, 9). Perhaps the biggest health concern remains the potential for drinking water contamination from fracturing fluids, natural formation waters, and stray gases (4, 10–12).

Despite public concerns over possible water contamination, only a few studies have examined drinking water quality related to shale gas extraction (4, 11, 13). Working in the Marcellus region of Pennsylvania, we published peer-reviewed studies of the issue, finding no evidence for increased concentrations of salts, metals, or radioactivity in drinking water wells accompanying shale gas extraction (4, 11). We did find higher methane concentrations and less negative $\delta^{13}C\text{-}CH_4$ signatures, consistent with a natural gas source, in water for homeowners living <1 km from shale gas wells (4). Here, we present a more extensive dataset for natural gas in shallow water wells in northeastern Pennsylvania, comparing the data with sources of thermogenic methane, biogenically derived methane, and methane found in natural seeps. We present comprehensive analyses for distance to gas wells and ethane and propane concentrations, two hydrocarbons that are not derived from biogenic activity and are associated only with thermogenic sources. Finally, we use extensive isotopic data [e.g., $\delta^{13}C\text{-}CH_4$, $\delta^{2}H\text{-}CH_4$, $\delta^{13}C\text{-}C_2H_6$, $\delta^{13}C$-dissolved inorganic carbon ($\delta^{13}C$-DIC), and $\delta^{2}H\text{-}H_2O$] and helium analysis ($^4He/CH_4$) to distinguish among different sources for the gases observed (14–16).

Our study area (Figs. S1 and S2) is within the Appalachian Plateaus physiographic province (17, 18) and includes six counties in Pennsylvania (Bradford, Lackawanna, Sullivan, Susquehanna, Wayne, and Wyoming). We sampled 81 new drinking water wells from the three principle aquifers (Alluvium, Catskill, and Lock Haven) (Fig. S1) (11). We combined the data with results from 60 previously sampled wells in Pennsylvania (4) and included a few wells from the Genesee Formation in Otsego County of New York (4). The typical depth of drinking water wells in our study was 60–90 m (11). We also sampled a natural methane seep at Salt Springs State Park in Franklin Forks, Pennsylvania (N 41.91397, W 75.8663; Susquehanna County) to compare with drinking water from homes in our study, some located within a few kilometers of the spring.

Descriptions of the underlying geology, including the Marcellus Formation found 1,500–2,500 m underground, are presented in refs. 4 and 11 and Fig. S2. Previous researchers have characterized the region's geology and aquifers (19–23). Briefly, the two major bedrock aquifers are the Upper Devonian Catskill Formation, comprised primarily of a deltaic clastic wedge gray-green to gray-red sandstone, siltstone, and shale, and the underlying Lock Haven Formation, consisting of interbedded fine-grained sandstone, siltstone, and silty shale (19, 22, 24). The two formations can be as deep as ~1,000 m in the study area and have been exploited elsewhere for oil and gas historically. The sedimentary sequences are gently folded and dip shallowly (1–3°) to the east and south (Fig. S2), creating alternating exposures of synclines and anticlines at the surface (17, 23, 25). These formations are overlain by the Alluvium aquifer, comprised of unconsolidated glacial till, alluvium sediments, and postglacial deposits found primarily in valley bottoms (20, 22).

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Author contributions: R.B.J., A.V., T.H.D., N.R.W., and A.D. designed research; R.B.J., A.V., T.H.D., N.R.W., A.D., R.J.P., S.G.O., K.Z., and J.D.K. performed research; R.B.J., A.V., T.H.D., N.R.W., A.D., R.J.P., K.Z., and J.D.K. analyzed data; and R.B.J., A.V., T.H.D., N.R.W., and A.D. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1221635110/-/DCSupplemental.

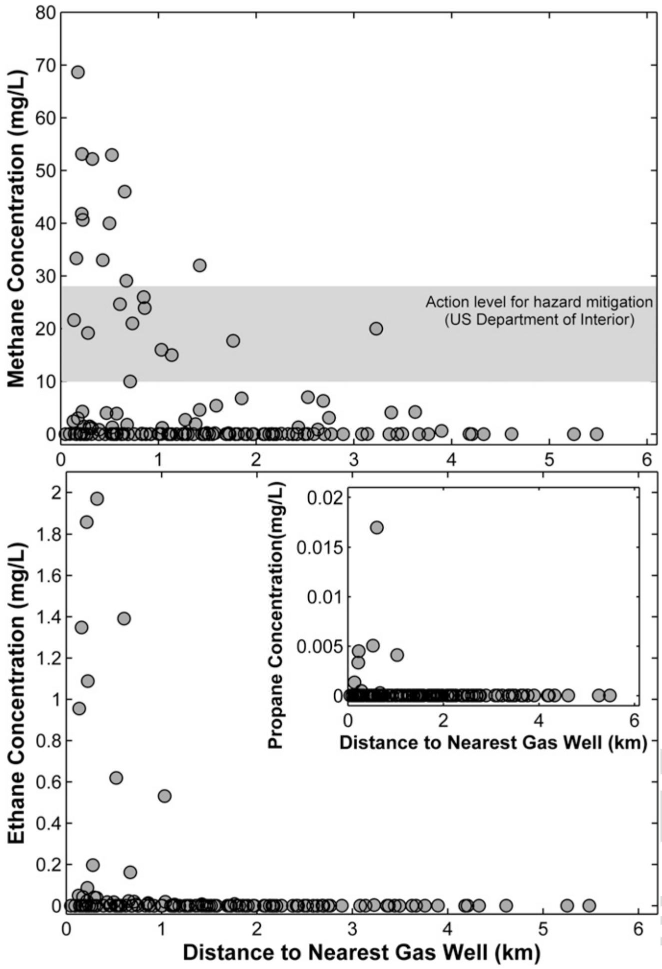

**Fig. 1.** Concentrations of (*Upper*) methane, (*Lower*) ethane, and (*Lower Inset*) propane (milligrams liter$^{-1}$) in drinking water wells vs. distance to natural gas wells (kilometers). The locations of natural gas wells were obtained from the Pennsylvania DEP and Pennsylvania Spatial Data Access databases (54). The gray band in *Upper* is the range for considering hazard mitigation recommended by the US Department of the Interior (10–28 mg $CH_4$/L); the department recommends immediate remediation for any value >28 mg $CH_4$/L.

## Results and Discussion

Dissolved methane was detected in the drinking water of 82% of the houses sampled (115 of 141). Methane concentrations in drinking water wells of homes <1 km from natural gas wells (59 of 141) were six times higher on average than concentrations for homes farther away ($P = 0.0006$, Kruskal–Wallis test) (Fig. 1 and Fig. S3). Of 12 houses where $CH_4$ concentrations were greater than 28 mg/L (the threshold for immediate remediation set by the US Department of the Interior), 11 houses were within 1-km distance of an active shale gas well (Fig. 1). The only exception was a home with a value of 32 mg $CH_4$/L at 1.4-km distance.

Similar to the results for methane, concentrations of ethane ($C_2H_6$) and propane ($C_3H_8$) were also higher in drinking water of homes near natural gas wells (Fig. 1). Ethane was detected in 40 of 133 homes (30%; 8 fewer homes were sampled for ethane and propane than for methane). Propane was detected in water wells in 10 of 133 homes, all approximately <1 km from a shale gas well ($P = 0.01$) (Fig. 1, *Lower Inset*). Ethane concentrations were 23 times higher on average for homes <1 km from a gas well: 0.18 compared with 0.008 mg $C_2H_6$/L ($P = 0.001$, Kruskal–Wallis). Seven of eight $C_2H_6$ concentrations >0.5 mg/L were found <1 km from a gas well (Fig. 1), with the eighth point only 1.1 km away (Fig. 1). Moreover, the higher ethane concentrations all occurred in groundwater with methane concentrations >15 mg/L ($P = 0.003$ for the regression of $C_2$ and $C_1$) (Fig. S4), although not all higher methane concentration waters had elevated ethane.

Ratios of ethane to methane ($C_2/C_1$) and propane to methane ($C_3/C_1$) were much higher for homes within ~1 km of natural gas wells (Fig. 2). Our high $C_3/C_1$ samples were also an order of magnitude greater than in salt-rich waters from a natural methane seep at the nearby Salt Springs State Park (mean $[C_3]/[C_1] = 0.000029$ and $[C3] = 0.0022$ mg/L for the salt spring samples). Because microbes effectively do not produce ethane or propane in the subsurface (26, 27), our observed values within ~1 km of drilling seem to rule out a biogenic methane source, and they are consistent with both wetter (higher $C_2 + C_3$ content) gases found in the Marcellus Formation and our earlier observation of methane in drinking water wells in the region (4).

Along with distance to gas wells (4), proximity to both valley bottom streams (i.e., discharge areas) (28) and the Appalachian Structural Front (ASF; an index for the trend in increasing thermal maturity and degree of tectonic deformation) has been suggested to influence dissolved gas concentrations. Of these factors, distance to gas wells was the dominant statistical factor in our analyses for both methane ($P = 0.0007$) (Table 1, multiple regression analysis) and ethane ($P < 0.005$) (Table 1). In contrast, neither distance to the ASF ($P = 0.11$) nor distance to valley bottom streams ($P = 0.27$) was significant for methane concentrations analysis using linear regression. For single correlation factors, distance to gas wells was again the dominant statistical term ($P = 0.0003$ and $P = 0.001$ for Pearson and Spearman coefficients, respectively). Distance to the ASF was slightly significant by Pearson and Spearman correlation analyses ($P = 0.04$ and $P = 0.02$, respectively), whereas distance to valley bottom streams was slightly significant only for the nonparametric Spearman analysis ($P = 0.22$ for Pearson and $P = 0.01$ for Spearman) (Table 1). For observed ethane concentrations, distance to gas wells was the only factor in our dataset that was statistically significant ($P < 0.005$, regardless of whether analyzed by multiple regression, Pearson correlation, or Spearman analyses) (Table 1).

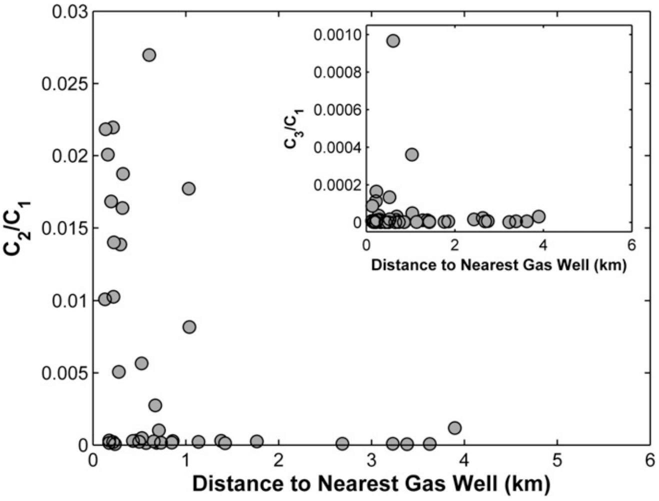

**Fig. 2.** The ratio of ethane to methane ($C_2/C_1$) and (*Inset*) propane to methane ($C_3/C_1$) concentrations in drinking water wells as a function of distance to natural gas wells (kilometers). The data are plotted for all cases where [$CH_4$], [$C_2H_6$], and [$C_3H_8$] were above detection limits or [$CH_4$] was >0.5 mg/L but [$C_2H_6$] or [$C_3H_8$] was below detection limits using the detection limits of 0.0005 and 0.0001 mg/L for [$C_2H_6$] and [$C_3H_8$], respectively.

**Table 1. Statistical analyses for [CH$_4$] and [C$_2$H$_6$]**

| | Distance to gas wells | Distance to streams | Distance to ASF |
|---|---|---|---|
| [CH$_4$] | | | |
| Multiple regression | $P = 0.0007$ | $P = 0.27$ | $P = 0.11$ |
| Pearson $r$ | $P = 0.0003$ | $P = 0.22$ | $P = 0.04$ |
| Spearman $\rho$ | $P = 0.007$ | $P = 0.01$ | $P = 0.02$ |
| [C$_2$H$_6$] | | | |
| Multiple regression | $P = 0.0034$ | $P = 0.053$ | $P = 0.45$ |
| Pearson $r$ | $P = 0.003$ | $P = 0.36$ | $P = 0.11$ |
| Spearman $\rho$ | $P = 0.004$ | $P = 0.95$ | $P = 0.21$ |

Isotopic signatures and gas ratios provide additional insight into the sources of gases in groundwater. Signatures of $\delta^{13}$C-CH$_4$ > −40‰ (reference to Vienna Pee Dee Belemnite standard) generally suggest a thermogenic origin for methane, whereas $\delta^{13}$C-CH$_4$ values < −60‰ suggest a biogenically derived methane source (27, 29, 30). Across our dataset, the most thermogenic $\delta^{13}$C-CH$_4$ signatures (i.e., most enriched in $^{13}$C) in drinking water were generally found in houses with elevated [CH$_4$] <1 km from natural gas wells (Fig. 3*A*). In fact, all drinking water wells with methane concentrations >10 mg/L, the US Department of Interior's threshold for considering remediation, have $\delta^{13}$C-CH$_4$ signatures consistent with thermogenic natural gas. Our data also show a population of homes near natural gas wells with water that has $\delta^{13}$C-CH$_4$ signatures that seem to be microbial in origin, specifically those homes shown in Fig. 3*A*, lower left corner. The combination of our $\delta^{13}$C-CH$_4$ (Fig. 3*A*) and $\delta^2$H-CH$_4$ data (Fig. 3*B*) overall, however, suggests that a subset of homes near natural gas wells has methane with a higher thermal maturity than homes farther away.

Analyses of $\delta^{13}$C-CH$_4$ and $\delta^{13}$C-C$_2$H$_6$ can help constrain potential sources of thermally mature natural gases (14, 15, 30). Because organic matter cracks to form oil and then natural gas, the gases initially are enriched in higher aliphatic hydrocarbons C$_2$ and C$_3$ (e.g., C$_3$ > C$_2$ > C$_1$; i.e., a relatively wet gas). With increasing thermal maturity, the heavier hydrocarbons are progressively broken down, increasing the C$_1$:C$_2^+$ ratio and leading to isotopic compositions that become increasingly heavier or enriched (31). In most natural gases, the isotopic composition ($\delta^{13}$C) of C$_3$ > C$_2$ > C$_1$ (i.e., $\delta^{13}$C of ethane is heavier than methane). In thermally mature black shales, however, this maturity trend reverses, creating diagnostic isotopic reversals in which the $\delta^{13}$C-CH$_4$ becomes heavier than $\delta^{13}$C-C$_2$H$_6$ ($\Delta^{13}$C = $\delta^{13}$C-CH$_4$ − $\delta^{13}$C-C$_2$H$_6$ > 1) (14, 15, 28, 30, 32).

For 11 drinking water samples in our dataset with sufficient ethane to analyze isotopic signatures, 11 samples were located <1.1 km from drilling, and 6 samples exhibited clear isotopic reversals similar to Marcellus production gases (Fig. 4). Conversely, five drinking water samples and spring water from Salt Springs State Park showed the more common trend consistent with Upper Devonian production gases (Fig. 4). In the study area, these isotopic values suggest multiple sources for hydrocarbon gases. The Upper Devonian gases are likely introduced into the shallow crust either by natural processes over geologic time or through leakage around the casing in the annular space of the production well. In contrast, natural gas with heavy $\delta^{13}$C-CH$_4$ and $\Delta^{13}$C > 0 likely stems from Marcellus production gases or a mixture of Marcellus gases and other annulus gases that migrated to the surface during drilling, well completion, or production.

Similar to our data, independent CH$_4$ measurements taken by the US Environmental Protection Agency (EPA) in Dimock, Pennsylvania (Residential Data Reports found at http://www.epaosc.org/site/doc_list.aspx?site_id=7555) in January of 2012 also show three $\delta^{13}$C-CH$_4$ values in drinking water wells between −24.98‰ and -29.36‰ $\delta^{13}$C-CH$_4$ and five samples with $\delta^{13}$C-CH$_4$ values in the range of Marcellus gas defined in ref. 28. The heaviest methane isotopic signatures in the EPA samples

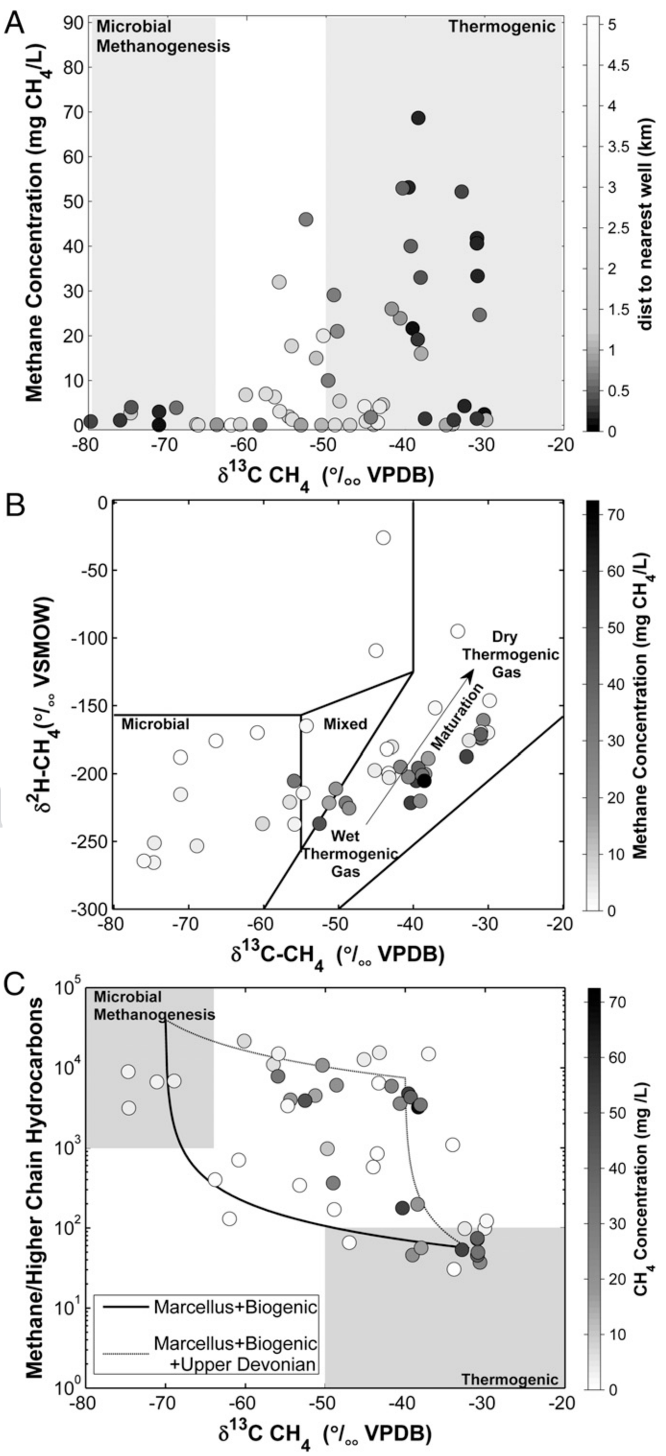

**Fig. 3.** (*A*) Methane concentration, (*B*) $\delta^2$H-CH$_4$, and (*C*) methane to ethane + propane ratio plotted against $\delta^{13}$C-CH$_4$. The grayscale shading refers to (*A*) distance to nearest gas wells and (*B* and *C*) methane concentration. The solid lines in *B* distinguishing natural gas sources are from ref. 27; the mixed line in *B* comes from the standard mixing equations in ref. 14. *C* shows two hypothetical trajectories: simple mixing between thermogenically and biogenically derived gas (lower curve) and either diffusive migration or a three-component mixture between Middle and Upper Devonian gases and shallow biogenic gases (upper curve).

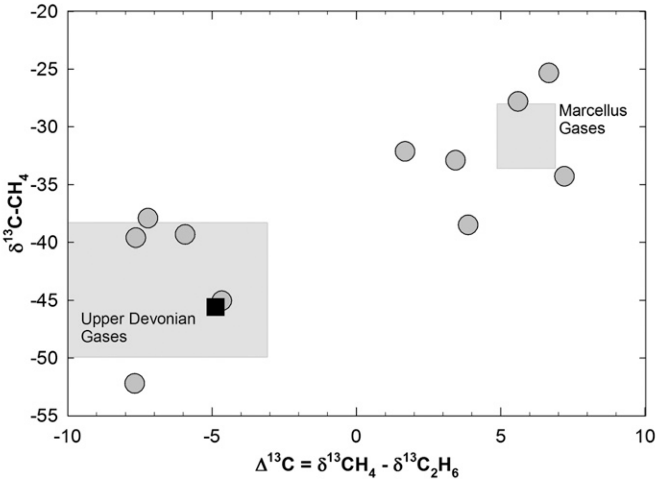

**Fig. 4.** Stable isotope signatures (‰ VPDB) of methane ($\delta^{13}C\text{-}CH_4$) vs. $\delta^{13}C$ for methane minus ethane ($\Delta^{13}C = \delta^{13}CH_4 - \delta^{13}C_2H_6$); 6 of 11 drinking water samples exhibited isotopic reversals and $\delta^{13}C\text{-}CH_4$ values consistent with Marcellus production gas (14, 28, 55). In contrast, five drinking water samples and the salt spring at Salt Springs State Park (filled square) had $\delta^{13}C\text{-}CH_4$ and $\Delta^{13}C < 0$ consistent with Upper Devonian production gases (14, 55). Eleven drinking water samples had sufficient ethane concentrations for isotopic determinations. Ten of the samples were <1 km distance from shale gas wells, and one sample is at 1.1 km distance (the point in the lower left corner of the plot).

(−24.98‰ $\delta^{13}C\text{-}CH_4$) exceeded the values observed for ethane (−31.2‰ $\delta^{13}C\text{-}C_2H_6$), an isotopic reversal ($\Delta^{13}C = 6.22$‰) characteristic of Marcellus or other deeper gas compared with gases from Upper Devonian sequences (14, 28).

Helium is an inert noble gas with a radiogenic isotope, $^4$He, that is a major component of thermogenic natural gas. Similar to hydrocarbon components, the abundance and isotopic composition of helium can help distinguish between potential sources and/or residence times of fluids in the crust, including natural gases (15, 16, 33). Across our dataset, the ratio of $^4He:CH_4$ in most drinking water wells showed a typical range between $\sim 2 \times 10^{-3}$ and $1 \times 10^{-2}$, independent of distance to natural gas wells (Fig. 5). In contrast, a subset of points with elevated $[CH_4]$ has a $^4He:CH_4$ ratio significantly below the range established for shallow drinking water in the region and consistent with a mixture between shallow groundwater and Marcellus production gases there ($\sim 2\text{–}5 \times 10^{-4}$) (Fig. 5) (15).

The relative proportions of methane to higher-chain hydrocarbons, such as ethane and propane, can also be used to help differentiate biogenically and thermogenically derived methane as well as different thermogenic sources of natural gas (34). As described above, low ratios of methane to higher-chain hydrocarbons (∼<100) in water typically suggest a hydrocarbon gas derived from a thermogenic source, whereas ratios of methane to higher-chain hydrocarbons >>1,000 suggest a microbial origin for the gas (27). Across our hydrocarbon dataset, ∼15 samples seem to fall within the range corresponding to thermogenic gas, whereas the composition of 5 or 6 samples seems to be microbial in origin (Fig. 3*C*). The other points fell on two intermediate trajectories. One trajectory is simple mixing between thermogenically and biogenically derived gas (lower curve in Fig. 3*C*). The other trajectory reflects either diffusive migration or a more complex, three-component mixture between Middle and Upper Devonian gases and shallow biogenic sources (30, 35) (upper trajectory in Fig. 3*C*).

The relative distribution of ethane and propane provides additional insight into the source and mixture of gases. The ratio of propane to methane concentrations plotted against $[C_3H_8]$ (Fig. S5) shows that at least 6 of 10 water samples with detectable $[C_3H_8]$ had an order of magnitude greater $[C_3]/[C_1]$ ratio and $[C_3]$ content than spring water from the natural methane seep at the Salt Springs State Park. The salt spring is the only location for which we found detectable $[C_3]$ outside of our 11 samples (mean $[C_3]/[C_1] = 0.000029$ and $[C3] = 0.0022$ mg/L for the Salt Springs samples) (Fig. S5).

The abundance and relative proportions of aliphatic hydrocarbons (i.e., propane and ethane) and methane in groundwater are also useful for comparing with production gases (14, 36) and samples from the Salt Springs State Park. Ratios of propane to ethane ($C_3/C_2$) in our dataset were generally higher than ratios for the Salt Springs State Park, and ratios of methane to ethane ($C_1/C_2$) were generally lower (Fig. S6), approaching ratios for Marcellus gases in some cases (Fig. S6). We also observed that the highest methane concentrations coincided with increased abundances of ethane and propane and a higher proportion of propane relative to ethane (Fig. S7). The observed gas composition in groundwater samples also had a substantially higher proportion of propane relative to ethane than water from the Salt Springs State Park, which is known to have historic methane-rich discharges (11, 37) (Fig. S7). Based on limited available production data, the Marcellus production gases have a wetness ($C_2 + C_3$) of at least 1–2% and $C_3/C_2$ of ∼>0.03%, whereas Upper Devonian gases, specifically those gases observed in Upper Devonian aquifers before shale gas development (30), tend to be relatively depleted in wetter gases; samples from the Salt Springs State Park had intermediate wetness, which is discussed above (14, 30). As a result, increasing proportions of $C_3/C_2$ tend to be more representative of gases from Marcellus-producing wells (Fig. S6) than Upper Devonian Formations or Salt Springs State Park.

An enrichment of $^{13}$C in DIC (e.g., $\delta^{13}C\text{-DIC} > +10$‰) and positive correlations between $\delta^{13}C\text{-DIC}$ and $\delta^{13}C\text{-}CH_4$ and between $\delta^{2}H\text{-}H_2O$ and $\delta^{2}H\text{-}CH_4$ have all been used as indicators of microbial methane sourced from relatively shallow depths (∼<550 m) (38, 39). Most of our $\delta^{13}C\text{-DIC}$ values were 20–25‰ lighter (more negative) than typical for DIC influenced by microbially derived methane in shallow groundwater, and the $\delta^{13}C\text{-}CH_4$ values of the samples showed no evidence of a positive relationship with $\delta^{13}C\text{-DIC}$ (and even a slight negative relationship; $P = 0.003$) (Fig. S8, *Upper*). We also found no statistical relationship between the $\delta^2H$ values of methane and $\delta^2H$ of water (Fig. S8, *Lower*). Based on these data and similar to the observations in the work by Osborn et al. (4), most of the methane in our samples does not

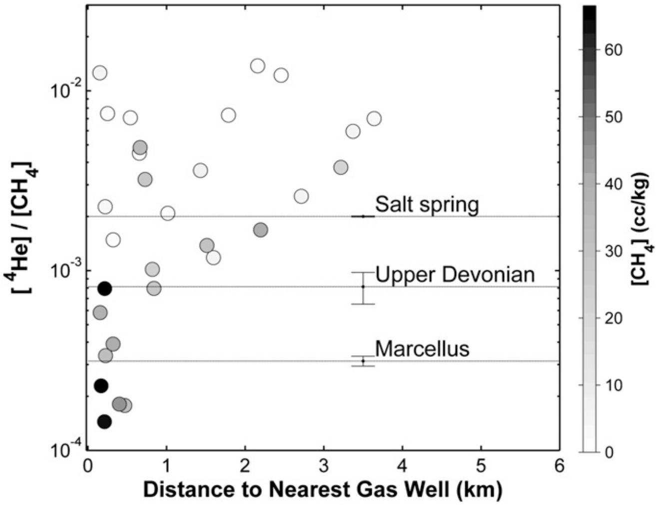

**Fig. 5.** The ratio of $^4He:CH_4$ concentrations in drinking water wells vs. distance to gas wells (kilometers). The values are compared with water samples (mean ± SE) from the salt spring at Salt Springs State Park (*n* = 3) and Marcellus (*n* = 4) and Upper Devonian (*n* = 5) production gases (15).

seem to be derived locally in the shallow aquifers, and the gas composition is not consistent with extensive microbial production from methanogenesis or sulfate reduction. Methanotrophy also does not seem to be occurring broadly across our dataset; it would decrease [$CH_4$] and $C_1$:$C_2$ ratios and increase $\delta^{13}CH_4$ values, reducing the differences that we observed for distance to gas wells. Overall, the combined results suggest that natural gas, derived at least in part from thermogenic sources consistent with Middle Devonian origin, is present in some of the shallow water wells <1 km away from natural gas wells.

The two simplest explanations for the higher dissolved gas concentrations that we observed in drinking water are (*i*) faulty or inadequate steel casings, which are designed to keep the gas and any water inside the well from leaking into the environment, and (*ii*) imperfections in the cement sealing of the annulus or gaps between casings and rock that keep fluids from moving up the outside of the well (4, 40–42). In 2010, the Pennsylvania Department of Environmental Protection (DEP) issued 90 violations for faulty casing and cementing on 64 Marcellus shale gas wells; 119 similar violations were issued in 2011.

Distinguishing between the two mechanisms is important because of the different contamination to be expected through time. Casing leaks can arise from poor thread connections, corrosion, thermal stress cracking, and other causes (43). If the protective casing breaks or leaks, then stray gases could be the first sign of contamination, with less mobile salts and metals from formation waters or chemicals from fracturing fluids potentially coming later. In contrast, faulty cement can allow methane and other gases from intermediate layers to flow into, up, and out of the annulus into shallow drinking water layers. In such a scenario, the geochemical and isotopic compositions of stray gas contamination would not necessarily match the target shale gas, and no fracturing chemicals or deep formation waters would be expected, because a direct connection to the deepest layers does not exist; also, such waters are unlikely to migrate upward. Comprehensive analyses of well integrity have shown that sustained casing pressure from annular gas flow is common. A comprehensive analysis of ∼15,500 oil and gas wells (43) showed that 12% of all wells drilled in the outer continental shelf area of the Gulf of Mexico had sustained casing pressure within 1 y of drilling, and 50–60% of the wells had it from 15 y onward. For our dataset, there is a weak trend to higher methane concentrations with increasing age of the gas wells ($P = 0.067$ for [$CH_4$] vs. time since initial drilling). This result could mean that the number of drinking water problems may grow with time or that drilling practices are improving with time; more research is needed before firm conclusions can be drawn.

In addition to well integrity associated with casings or cementing, two other potential mechanisms for contamination by hydraulic fracturing/horizontal drilling include enhancing deep-to-shallow hydraulic connections and intersecting abandoned oil and gas wells. Horizontal drilling and hydraulic fracturing can stimulate fractures or mineralized veins, increasing secondary hydraulic connectivity. The upward transport of gases is theoretically possible, including pressure-driven flow through open, dry fractures and pressure-driven buoyancy of gas bubbles in aquifers and water-filled fractures (44, 45). Reduced pressures after the fracturing activities could also lead to methane exsolving rapidly from solution (46). If methane were to reach an open fracture pathway, however, the gas should redissolve into capillary-bound water and/or formation water, especially at the lithostatic and hydrostatic pressures present at Marcellus depths. Legacy or abandoned oil and gas wells (and even abandoned water wells) are another potential path for rapid fluid transport. In 2000, the Pennsylvania DEP estimated that it had records for only 141,000 of 325,000 oil and gas wells drilled historically in the state, leaving the status and location of ∼184,000 abandoned wells unknown (47). However, historical drilling activity is minimal in our study area of northeastern Pennsylvania, making this mechanism unlikely there.

This study examined natural gas composition of drinking water using concentration and isotope data for methane, ethane, propane, and $^4He$. Based on the spatial distribution of the hydrocarbons (Figs. 1 and 2), isotopic signatures for the gases (Figs. 3 and 4), wetness of the gases (Fig. 2 and Figs. S5, S6, and S7), and observed differences in $^4He$:$CH_4$ ratios (Fig. 5), we propose that a subset of homeowners has drinking water contaminated by drilling operations, likely through poor well construction. Future research and greater data disclosure could improve understanding of these issues in several ways. More research is needed across the Marcellus and other shale gas plays where the geological characteristics differ. For instance, a new study by Duke University and the US Geological Survey showed no evidence of drinking water contamination in a part of the Fayetteville Shale with a less fractured or tectonically deformed geology than the Marcellus and good confining layers above and below the drinking water layers (48). More extensive predrilling data would also be helpful. Additional isotopic tools and geochemical tracers are needed to determine the source and mechanisms of stray gas migration that we observed. For instance, a public database disclosing yearly gas compositions (molecular and isotopic $\delta^{13}C$ and $\delta^2H$ for methane and ethane) from each producing gas well would help identify and eliminate sources of stray gas (49). In cases where carbon and hydrogen isotopes may not distinguish deep Marcellus-derived methane from shallower, younger Devonian methane, the geochemistry of $^4He$ and other noble gases provides a promising approach (15, 50). Another research need is a set of detailed case studies of water-quality measurements taken before, during, and after drilling and hydraulic fracturing. Such studies are underway, including partnerships of EPA- and Department of Energy-based scientists and industry in Pennsylvania, Texas, and North Dakota. In addition to predrilling data, disclosure of data from mud-log gases and wells to regulatory agencies and ideally, publicly would build knowledge and public confidence. Ultimately, we need to understand why, in some cases, shale gas extraction contaminates groundwater and how to keep it from happening elsewhere.

## Methods

A total of 81 samples from drinking water wells were collected in six counties in Pennsylvania (Bradford, Lackawanna, Sullivan, Susquehanna, Wayne, and Wyoming), and results were combined with 60 previous samples described in the work by Osborn et al. (4). The samples were obtained from homeowner associations and contacts with the goal of sampling Alluvium, Catskill, and Lock Haven groundwater wells across the region. For analyses of $^4He$ (Fig. 5), samples from 30 drinking water wells were used to estimate concentration ratios of $^4He$:$CH_4$. Wells were purged to remove stagnant water and then monitored for pH, electrical conductance, and temperature until stable values were recorded. Samples were collected upstream of any treatment systems and as close to the water well as possible, preserved in accordance with procedures detailed in *SI Text*, and returned immediately to Duke University for analyses. The chemical and isotope ($\delta^{13}C$-DIC, $\delta^2H$-$H_2O$, and $\delta^{18}O$-$H_2O$) compositions of the collected waters were measured at Duke University's Environmental Stable Isotope Laboratory. Values of $\delta^{18}O$-$H_2O$ and $\delta^2H$-$H_2O$ were measured using temperature conversion elemental analysis/continuous flow isotope ratio MS using a ThermoFinnigan temperature conversion elemental analysis and Delta+XL mass spectrometer and normalized to Vienna Standard Mean Ocean Water (analytical precision of ± 0.1‰ and ±1.5‰ for $\delta^{18}O$-$H_2O$ and $\delta^2H$-$H_2O$, respectively). Samples of $^4He$ were collected in refrigeration-grade copper tubes flushed with water before sealing with stainless steel clamps and analyzed using a VG 5400 MS at the University of Rochester (15, 51).

Dissolved gas samples were collected in the field using procedures detailed by Isotech Laboratories (52), stored on ice until delivery to their facilities, and analyzed for concentrations and isotopic compositions of methane, ethane, and propane. Procedures for gas analyses are summarized in ref. 4. Isotech Laboratories uses chromatographic separation followed by combustion and dual-inlet isotope ratio MS to measure dissolved gas concentrations, $\delta^{13}C$-$CH_4$, and $\delta^{13}C$-$C_2H_6$ (detection limits for $C_1$, $C_2$, and $C_3$ were 0.001, 0.0005, and 0.0001 mol %, respectively). Dissolved [$CH_4$] and $\delta^{13}C$-$CH_4$ were also determined by cavity ring-down spectroscopy in the Duke Environmental Stable Isotope Laboratory on eight samples using a Picarro G2112i.

Dissolved [$CH_4$] was equilibrated using a head-space equilibration method (53) and diluted when necessary using zero air. A set of 33 groundwater samples with a range of [$CH_4$] and $\delta^{13}C$-$CH_4$ was collected in duplicate and analyzed at both Duke University and Isotech Laboratories (Fig. S9). Hydrocarbon concentrations in groundwater were converted to milligrams of $CH_4$ $L^{-1}$ from a correlation with mol % ($R^2 = 0.95$). As in refs. 4 and 11, the derived distances to gas wells represent planimetric lengths from sampling locations to nearest gas wells and do not account for the direction or extent of horizontal drilling underground. Distances to streams were determined as the shortest lengths from sampled locations to valley centerlines using the national stream network as the base map; distance to the Appalachian Structural Front was measured using GIS software. Statistical analyses were performed using MATLAB and R software.

**ACKNOWLEDGMENTS.** W. Chameides, the Jackson laboratory, and anonymous reviewers provided helpful suggestions on the work. We acknowledge financial support from the Nicholas School of the Environment and Center on Global Change and Fred and Alice Stanback to the Nicholas School. We thank William Chameides, Dean of the Nicholas School, for supporting this research.

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# Supporting Information

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### SI Text

**Geological Setting.** The study area (Fig. S1) was chosen because of its rapid expansion of drilling for natural gas from the Marcellus Shale (Pennsylvania); also, it has a limited history of prior oil and gas exploration. Additionally, the study area represents portions of both the upper Susquehanna and upper Delaware watersheds that provide drinking water to >15 million people. The geological setting and methods for the work have been described previously in the works by Osborn et al. (1) and Warner et al. (2). Briefly, the sedimentary geology represents periods of deposition, burial, lithification, uplift, and subsequent erosion that form relatively simple sets of horizontal strata dipping 1° to 3° to the south and east derived from depositional environments that ranged from proposed deep to midbasin black shales to terrestrial red beds (3–5). The monocline is bounded on the north by the Precambrian Canadian Shield and Adirondack uplift (north to northeast), the west by the Algonquin and Findlay arches, and the south and east by the Appalachian fold belt (the Valley and Ridge Province) (6, 7). In general, sedimentary deposition in the northern Appalachian Basin was relatively continuous throughout the Paleozoic era. However, several unconformities erase sequence records regionally, such as the Tri-States unconformity that removed Lower Devonian strata in western New York, but complete sequences are generally found in central New York and our study region of northeastern Pennsylvania (3).

The Appalachian Basin consists primarily of sedimentary sequences of Ordovician to Pennsylvanian age that are derived from the Taconic (~450 Ma), Acadian (~410–380 Ma), and Alleghanian (~330–250 Ma) orogenic events (8). Exposed at its northern extent near Lake Ontario is the Upper Ordovician–Lower Silurian contact (Cherokee unconformity). Younger deposits (Upper Silurian, Devonian, and Mississippian) occur in successive outcrop belts to the south to the Appalachian structural front (4, 9), whereas erosion has removed most post-Pennsylvanian deposition within western-central New York and most of our study area within northeastern Pennsylvania. Bedrock thickness within the basin ranges from ~920 m along the southern shore of Lake Ontario in northern New York to ~7,600 m along the Appalachian structural front to the south. A simplified stratigraphic reconstruction is presented in Fig. S2 for the study area, which constitutes a transition from the Valley and Ridge to the Plateau Province. Compared with the Valley and Ridge Province or the region near the Appalachian Structural Front, the plateau portion of the Marcellus Formation is significantly less deformed (10). Deformation began during the onset of the Alleghanian orogeny. In the plateau physiographic province, deformation is accommodated by a combination of layer parallel shortening, folding that led to low-amplitude anticline/syncline sequences, low angle thrust faulting structures, lineaments, joints, and natural fractures observable in northeastern Pennsylvania (4, 11, 12).

The Marcellus Formation is an organic-rich, hydrocarbon-producing, siliciclastic-rich black shale present beneath much of Pennsylvania, New York, West Virginia, and other northeastern states. It constitutes the stratigraphically lowest subgroup of the Middle Devonian Hamilton Group (5, 9) and was deposited in the foreland basin of the Acadian Orogeny (~385–375 Ma). The Marcellus Formation includes two distinct calcareous and iron-rich black shale members [i.e., the Union Springs (lower) and Mount Marion/Oatka Creek (upper)) interrupted by the Cherry Valley limestone].

Like the Marcellus, the upper part of the Devonian sequence is deposited in the foreland basin of the Acadian Orogeny and consists of material sourced from the Acadian orogeny as part of the Catskill Deltaic sequence. Above the Marcellus, the Hamilton Group consists of the Mahantango gray shale locally interbedded by limestones and the Tulley limestone. The Upper Devonian consists of thick synorogenic sequences of gray shales (i.e., the Brallier Formation) beneath the Lock Haven Formation sandstone and Catskill Formation clastic deltaic red sandstones. The Lock Haven and Catskill Formations constitute the two primary aquifer lithologies in northeastern Pennsylvania along with the overlying glacial and sedimentary alluvium, which is thicker in valleys than the uplands.

Additional geological information is in the work by Osborn et al. (1) and references therein and the work by Warner et al. (2) and references therein.

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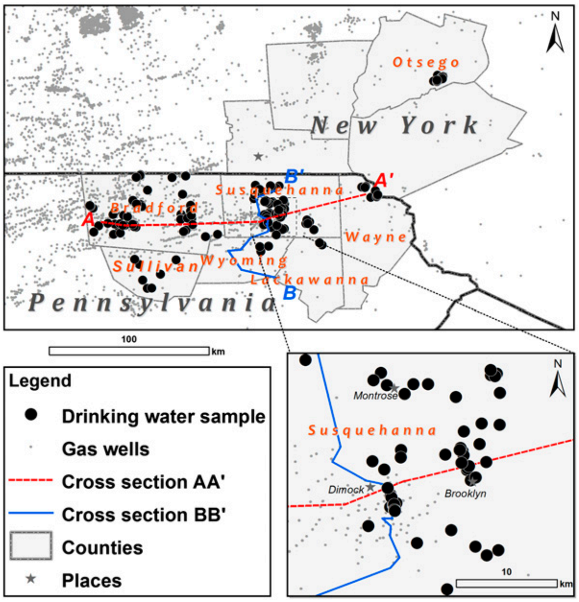

**Fig. S1.** Map of well water sampling locations in Pennsylvania and New York. The star in *Upper* represents the location of Binghamton, New York. (*Lower Right*) A close-up view of Susquehanna County, Pennsylvania. The stars in *Lower Right* represent the towns of Dimock, Brooklyn, and Montrose, Pennsylvania. The red and blue lines represent the approximate location of the cross-sections in Fig. S2.

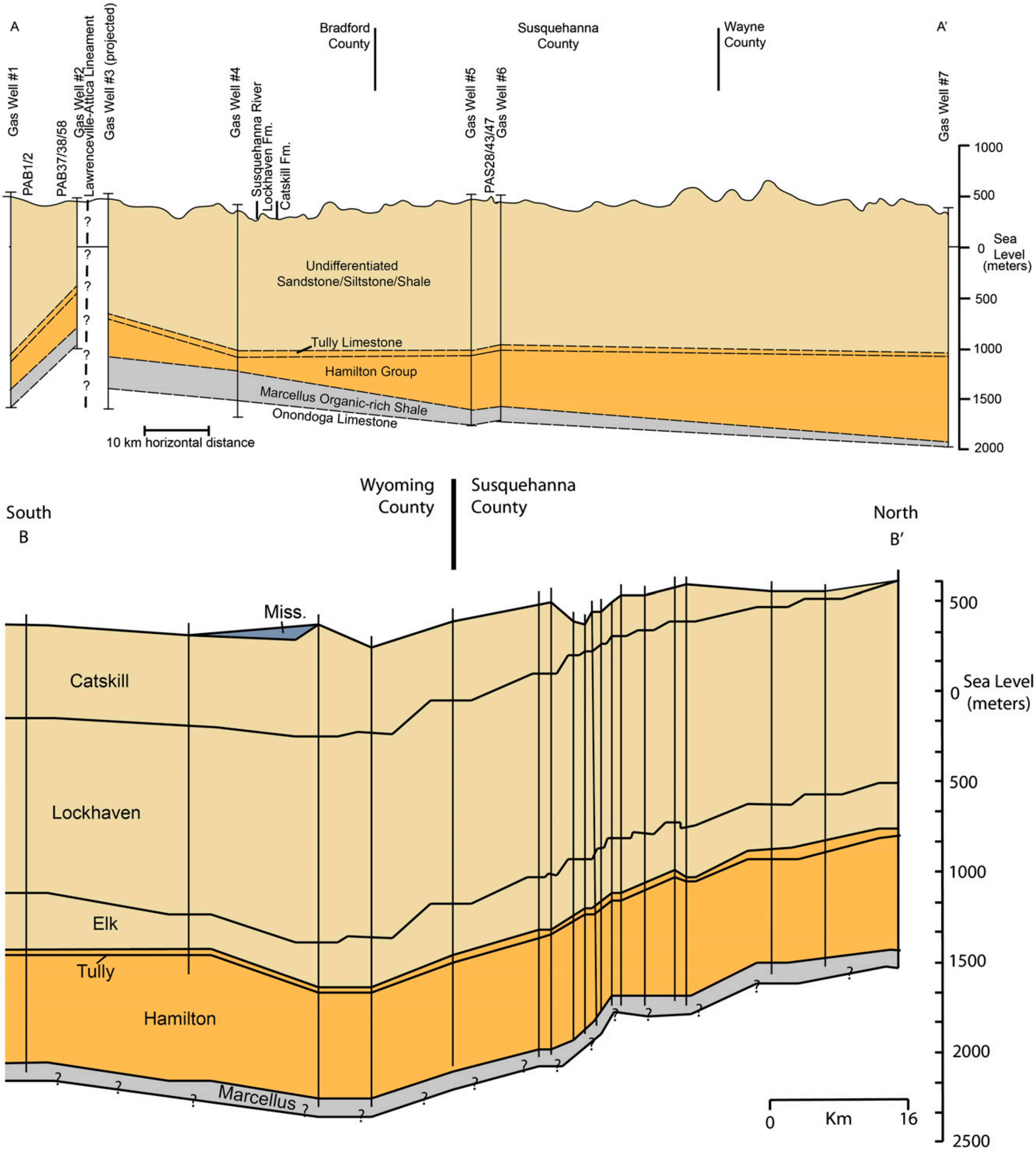

**Fig. S2.** Generalized stratigraphic section of the study region from the work by Osborn et al. (1), Molofsky et al. (2), and Warner et al. (3) and references therein. The cross sections shown here refer to the locations identified in Fig. S1.

1. Osborn SG, Vengosh A, Warner NR, Jackson RB (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc Natl Acad Sci USA* 108(20):8172–8176.
2. Molofsky LJ, Connor JA, Wylie AS, Wagner T, Farhat SK (2013) Evaluation of methane sources in groundwater in northeastern Pennsylvania. *Groundwater* 51(3):333–349.
3. Warner NR, et al. (2012) Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *Proc Natl Acad Sci USA* 109(30): 11961–11966.

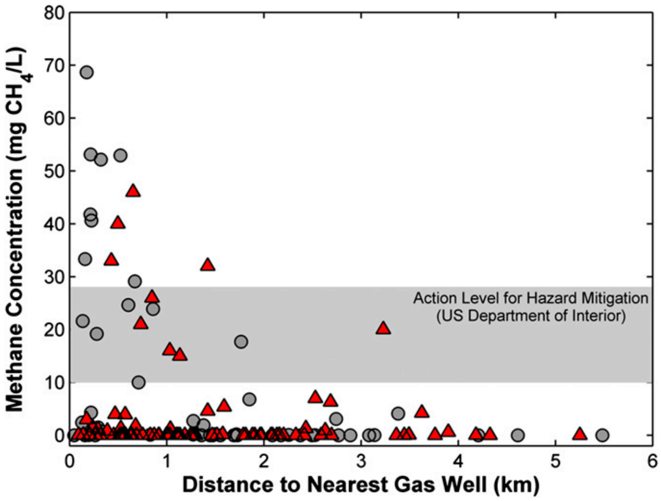

**Fig. S3.** Methane concentrations (milligrams per liter) vs. distance to nearest gas wells (kilometers) with data from the initial study (1) in filled circles and new observations in red triangles.

1. Osborn SG, Vengosh A, Warner NR, Jackson RB (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc Natl Acad Sci USA* 108(20):8172–8176.

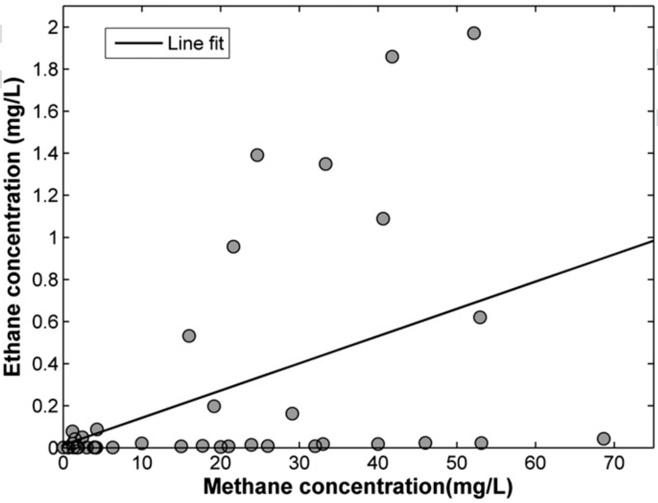

**Fig. S4.** Concentrations of ethane vs. methane across the groundwater dataset ($P = 0.0034$; $R^2 = 0.205$).

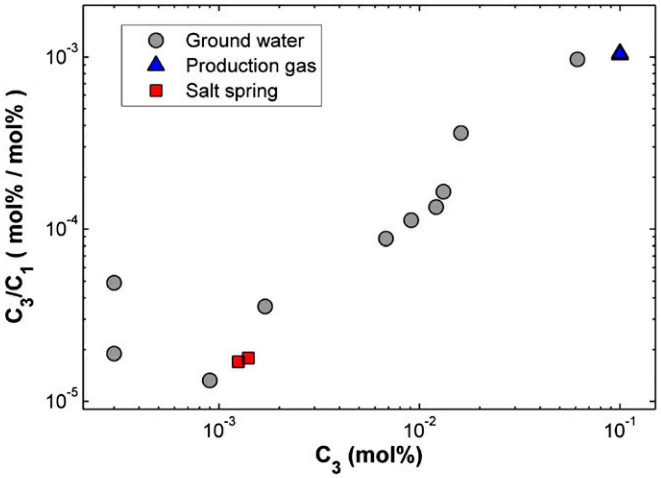

**Fig. S5.** The ratio of propane to methane concentrations vs. propane concentrations (mol%) for our data from drinking water wells (filled circles), the salt spring at Salt Springs State Park in Franklin Forks, Pennsylvania (red squares), and Marcellus production gas (blue triangle) (1).

1. Jenden PD, Drazan DJ, Kaplan IR (1993) Mixing of thermogenic natural gases in Northern Appalachian Basin. *Am Assoc Pet Geol Bull* 77(6):980–998.

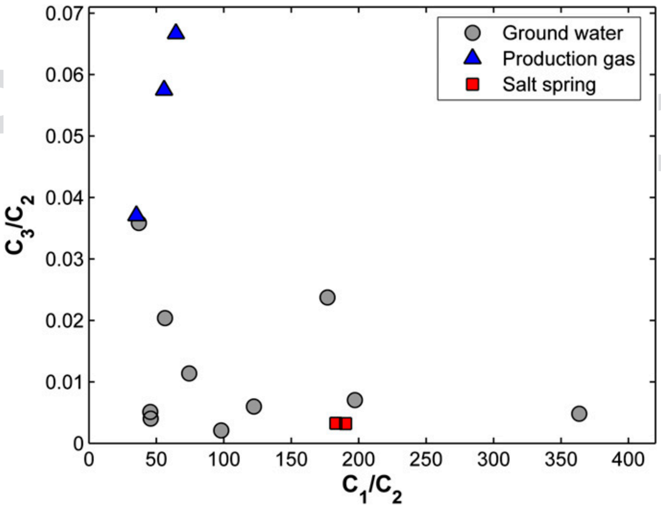

**Fig. S6.** The ratios of propane to ethane ($C_3/C_2$) and methane to ethane ($C_1/C_2$) concentrations for our data from drinking water wells (filled circles), the salt spring at Salt Springs State Park in Franklin Forks, Pennsylvania (red squares), and Marcellus production wells across the study area (blue triangles) (1, 2).

1. Jenden PD, Drazan DJ, Kaplan IR (1993) Mixing of thermogenic natural gases in Northern Appalachian Basin. *Am Assoc Pet Geol Bull* 77(6):980–998.
2. Laughrey CD, Baldassare FJ (1998) Geochemistry and origin of some natural gases in the Plateau province, central Appalachian basin, Pennsylvania and Ohio. *Am Assoc Pet Geol Bull* 82(2):317–335.

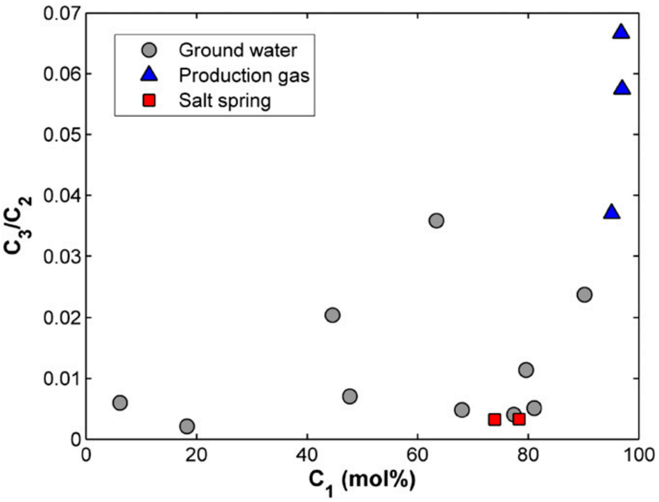

**Fig. S7.** The ratio of propane to ethane concentrations vs. methane concentrations (mol%) for our data from drinking water wells (filled circles), the salt spring at Salt Springs State Park in Franklin Forks, Pennsylvania (red squares), and production gases in the area (blue triangles) (1, 2).

1. Jenden PD, Drazan DJ, Kaplan IR (1993) Mixing of thermogenic natural gases in Northern Appalachian Basin. *Am Assoc Pet Geol Bull* 77(6):980–998.
2. Laughrey CD, Baldassare FJ (1998) Geochemistry and origin of some natural gases in the Plateau province, central Appalachian basin, Pennsylvania and Ohio. *Am Assoc Pet Geol Bull* 82(2):317–335.

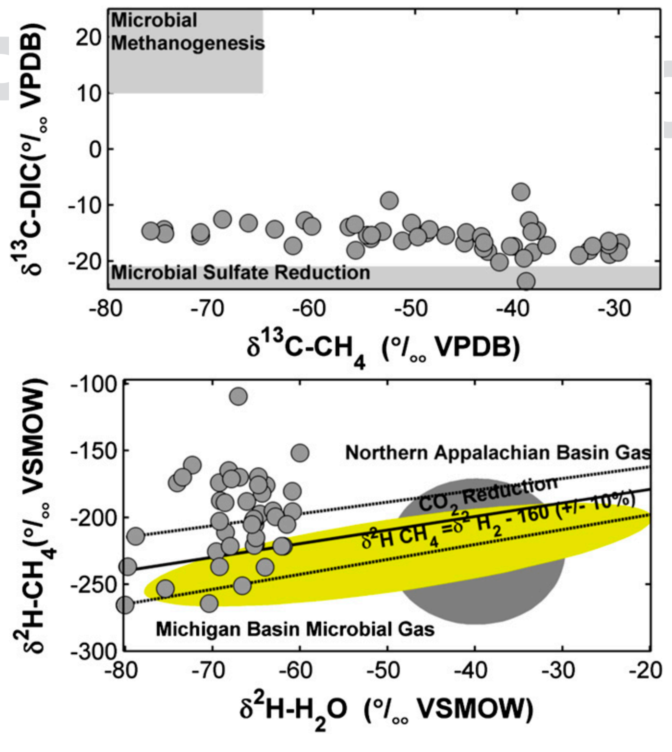

**Fig. S8.** (*Upper*) Plot of the carbon isotopes in $\delta^{13}C$ dissolved inorganic carbon ($\delta^{13}C$-DIC) in groundwater vs. carbon isotopes in coexisting methane ($\delta^{13}C$-$CH_4$), which illustrates that samples do not plot within methanogenesis or sulfate reduction zones. Ranges in $\delta^{13}C$-DIC for methanogenesis and sulfate reduction are taken from the work by Clark and Fritz (1). VPDB, Vienna Pee Dee belemnite. (*Lower*) Plot of $\delta^{2}H$-$CH_4$ of dissolved methane in groundwater vs. $\delta^{2}H$-$H_2$ of the groundwater. The fractionation line for microbial methanogenesis by $CO_2$ reduction depicted is from the work by Whiticar et al. (2). Microbial methane from the Michigan and Illinois Basins is depicted with the yellow oval (3, 4). Northern Appalachian Basin data are depicted in the gray oval (5). The lack of positive correlation between the two hydrogen sources indicates that microbial methane is negligible in the shallow groundwater. VSMOW, Vienna Standard Mean Ocean Water.

1. Clark ID, Fritz P (1997) *Environmental Isotopes in Hydrogeology* (Lewis, New York).
2. Whiticar MJ, Faber E, Schoell M (1986) Biogenic methane formation in marine and freshwater environments: $CO_2$ reduction vs. acetate fermentation—isotope evidence. *Geochim Cosmochim Acta* 50(5):693–709.
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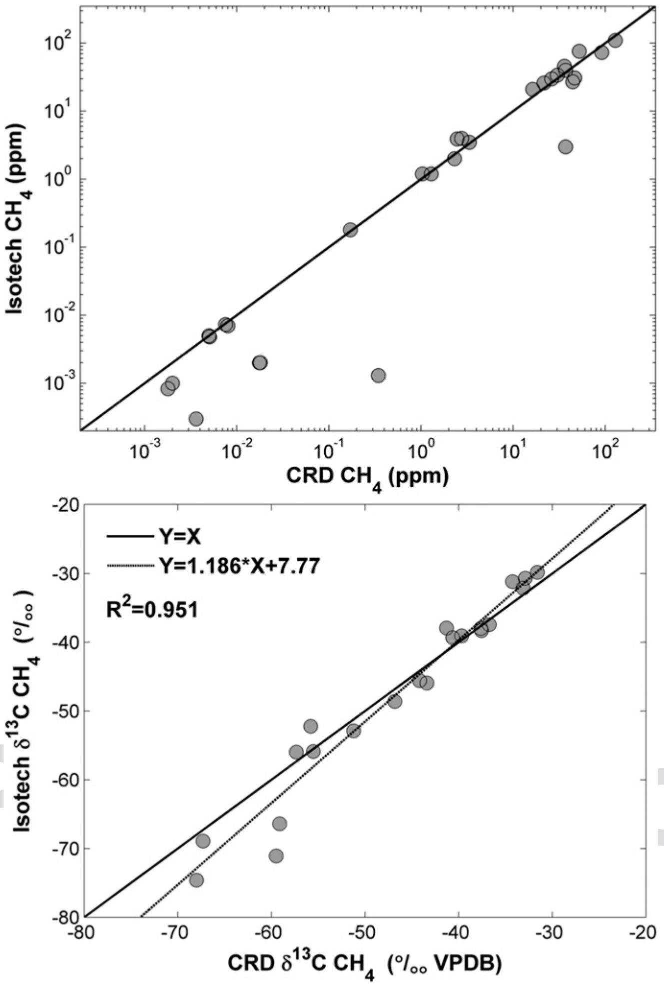

**Fig. S9.** Comparisons of Isotech Laboratories and cavity-ring down (CRD) spectrometry analyses for (*Upper*) [CH$_4$] and (*Lower*) δ$^{13}$C-CH$_4$ analyzed in duplicate at both Isotech Laboratories and the Duke Environmental Stable Isotope Laboratory. These results show statistically indistinguishable differences between the two data analysis methods.

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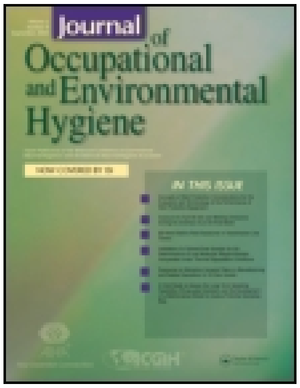

Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uoeh20

# Occupational Exposures to Respirable Crystalline Silica During Hydraulic Fracturing

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Accepted author version posted online: 26 Mar 2013.Published online: 16 May 2013.

**To cite this article:** Eric J. Esswein , Michael Breitenstein , John Snawder , Max Kiefer & W. Karl Sieber (2013) Occupational Exposures to Respirable Crystalline Silica During Hydraulic Fracturing, Journal of Occupational and Environmental Hygiene, 10:7, 347-356, DOI: 10.1080/15459624.2013.788352

**To link to this article:** http://dx.doi.org/10.1080/15459624.2013.788352

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*Journal of Occupational and Environmental Hygiene*, 10: 347–356
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459624.2013.788352

# Occupational Exposures to Respirable Crystalline Silica During Hydraulic Fracturing

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*This report describes a previously uncharacterized occupational health hazard: work crew exposures to respirable crystalline silica during hydraulic fracturing. Hydraulic fracturing involves high pressure injection of large volumes of water and sand, and smaller quantities of well treatment chemicals, into a gas or oil well to fracture shale or other rock formations, allowing more efficient recovery of hydrocarbons from a petroleum-bearing reservoir. Crystalline silica ("frac sand") is commonly used as a proppant to hold open cracks and fissures created by hydraulic pressure. Each stage of the process requires hundreds of thousands of pounds of quartz-containing sand; millions of pounds may be needed for all zones of a well. Mechanical handling of frac sand creates respirable crystalline silica dust, a potential exposure hazard for workers. Researchers at the National Institute for Occupational Safety and Health collected 111 personal breathing zone samples at 11 sites in five states to evaluate worker exposures to respirable crystalline silica during hydraulic fracturing. At each of the 11 sites, full-shift samples exceeded occupational health criteria (e.g., the Occupational Safety and Health Administration calculated permissible exposure limit, the NIOSH recommended exposure limit, or the ACGIH threshold limit value), in some cases, by 10 or more times the occupational health criteria. Based on these evaluations, an occupational health hazard was determined to exist for workplace exposures to crystalline silica. Seven points of dust generation were identified, including sand handling machinery and dust generated from the work site itself. Recommendations to control exposures include product substitution (when feasible), engineering controls or modifications to sand handling machinery, administrative controls, and use of personal protective equipment. To our knowledge, this represents the first systematic study of work crew exposures to crystalline silica during hydraulic fracturing. Companies that conduct hydraulic fracturing using silica sand should evaluate their operations to determine the potential for worker exposure to respirable crystalline silica and implement controls as necessary to protect workers.*

*[Supplementary materials are available for this article. Go to the publisher's online edition of* Journal of Occupational and Environmental Hygiene *for the following free supplemental resource: a file containing controls and recommendations to limit worker exposures to respirable crystalline silica at hydraulic fracturing work sites.]*

**Keywords** completions operations, crystalline silica, hydraulic fracturing, oil and gas extraction, sand

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## INTRODUCTION

Occupational exposure to respirable crystalline silica is a well-established hazard in mining, sandblasting, foundry work, agriculture, and construction, but not for oil and gas extraction work, which includes hydraulic fracturing.(1–9) Hydraulic fracturing involves high pressure injection of large volumes of water ($\approx$95% of total volume) "proppant" ($\approx$ 4.5%, typically as silica sand) and lesser quantities ($\leq$1.0%) of treatment chemicals (commonly a combination of surfactants, acids, scale inhibitor, clay stabilizers, corrosion/precipitation inhibitors, pH adjusting agents, gels, gel breakers, and biocides) into hydrocarbon-bearing strata to enhance recovery of oil and gas, particularly from deep shale formations. Hydraulic fracturing creates and enhances cracks and fissures in the geology; proppant holds the fractures open, allowing more efficient and sustained flow back of gas or oil.

Also called "well stimulation," "pressure pumping," or "completions operations," hydraulic fracturing has been used since the 1940s and has increased substantially over the last 10 years with the advent of "unconventional" drilling techniques (e.g., directional and horizontal) to access oil and gas not previously feasible with vertical drilling techniques alone.

Although silica sand is the most commonly used proppant, aluminum pellets, sintered bauxite, man-made ceramics, and resin-coated sand can also be used depending on geological conditions.(10,11)

Onshore oil and gas extraction (well drilling, servicing, and hydraulic fracturing) falls within the jurisdiction of the Occupational Safety and Health Administration (OSHA). Workplace safety hazards (e.g., risks for fatal injuries) in the upstream oil and gas extraction industry are documented, but to our knowledge, there are few (if any) published studies of chemical exposure risks for land-based crews during hydraulic fracturing operations.(12,13) Occupational health knowledge gaps in completions operations (i.e., hydraulic fracturing) include (1) understanding which job titles have risks for chemical exposures; (2) quantifying the magnitude of exposure risks (if present) for both chemicals and minerals; and (3) understanding the relative contribution of all likely route(s) of exposure, including inhalation, dermal exposures, and ingestion.

Approximately 435,000 workers were employed in the U.S. oil and gas extraction industry in 2010, nearly half employed by well servicing companies, including companies that conduct hydraulic fracturing.(14) To evaluate possible occupational health hazards, NIOSH initiated the Field Effort to Assess Chemical Exposures in Oil and Gas Extraction Workers in 2010. The work began with observations of completions work sites; reviews of safety data sheets; and discussions with work crews, supervisors, and health and safety personnel at hydraulic fracturing sites.(15) To date, exposure assessments for respirable crystalline silica during hydraulic fracturing have been the predominant focus of the NIOSH field effort.

## Crews and Machinery

At a typical site, 10–12 Driver/Operators position and set up equipment, configure and connect piping, pressure test, then operate the equipment (e.g., sand movers, blender, and chemical trucks) required for hydraulic fracturing. Other employees operate water tanks and water transport systems, and several control on-site traffic, including sand delivery trucks and other vehicles. An additional crew includes Wire Line (typically 3–5) who configure and assemble well casing perforation tools and operate cranes to move tools and equipment into and out of the well. Operators run the diesel-driven pump trucks necessary for hydraulic fracturing and operate sand movers and blender trucks to distribute and mix proppant (e.g., sand) and liquids. Chemical Truck Operators monitor and manage delivery of the necessary well treatment additives to the blender trucks for delivery to the well. Operationally, the entire process is monitored and controlled by personnel in on-site data vehicles with real-time monitoring of aboveground and in-well parameters, including temperatures, pressures, and flow rates of liquids and proppant.

On a typical 12-hr shift, workers may operate a specific piece of machinery (e.g., sand mover, blender truck) or may operate different machines over a shift. Roving Operators, Water Tank Operators, and Sand Coordinators/Ground Guides often work in different locations over a shift.

### *Sand Use, Transport, and Delivery in Modern, Unconventional Oil and Gas Extraction*

A typical unconventional gas or oil well has 12–20 stages (also called zones) that are fractured; some wells can have 40 or more stages. As stages increase, more water and proppant are required. Moving proppant along transfer belts, pneumatically filling and operating sand movers, involves displacement of hundreds of thousands of pounds of sand per stage, which creates airborne dusts at the work site.

Proppant (e.g., sand) is delivered to the well site by sand trucks (e.g., dry-bulk tractor trailers). Depending on the number of stages to be completed, delivery may consist of a single sand transfer or require serial proppant deliveries throughout the day. Sand trucks are offloaded by the Driver/Operator who connects the delivery truck to a sand holding/sand transport vehicle, hereafter called "sand mover," that uses compressed air to pump sand through fill ports on sides of sand movers; offloading takes 30 to 45 min.

Sand movers supply sand to blender trucks via a motor-driven belt assembly located beneath the mover. The assembly retracts and extends, elevates, and swings and is commonly referred to as the "dragon tail." Sand Mover Operator stations are located on top rear and side rear of the mover directly above and to the side of the dragon tail. Larger proppant loads are increasingly common, requiring multiple sand movers and a transfer or "T-belt" to convey sand between the sand mover and the blender truck. Sand Mover Operators control sand delivery by hydraulically controlling gates on the bottom of the sand mover and by manipulation of belt speed. Sand Mover Operators observe proppant being delivered into the blender hopper (or onto the T-belt) and communicate with Blender Operators and personnel in data monitoring vehicles. The intent is for the proppant to remain dry until it enters the wet section of the blender before pumping through a manifold, connection piping, and into the wellbore.

Despite differences in shape, size, color, and quality, all sand used for hydraulic fracturing consists of silicon, the second most abundant element in the earth's crust.(16) The most common crystalline form of silicon dioxide ($SiO_2$) is quartz.(16) Various types, sizes, colors, and treatments (e.g., Northern white; Texas yellow; 20/40, 40/70, and 100 mesh; plain vs. resin coated) of silica sand (typically 99% quartz) are used as the primary proppant for completions operations across the United States. Increased use and demand for silica sand proppant is expected to continue with ongoing completion operations in existing oil and gas basins and as operations increase across relatively newer, developing areas (e.g., Bakken formation in North Dakota and Niobrara in Northeast Colorado and parts of Kansas and Nebraska).(17) High-quality frac sand is typically defined as having consistent shape (sphericity), size, and compressive strength. The American Petroleum Institute (API) has developed specifications/standards (RP 56) for certain mesh sizes of frac sand.(18)

## Silica-Related Disease

Inhalation of respirable crystalline silica can cause silicosis, lung cancer, autoimmune disorders, kidney disease, and an increased risk of tuberculosis.(19–24) Although U.S. mortality statistics typically undercount silicosis cases, death certificates document that between 2000 and 2005 an average of 162 annual deaths from all occupations described silicosis as the proximal cause or a prevailing condition.(25,26)

The NIOSH recommended exposure limit (REL) for respirable crystalline silica is 0.05 milligrams of respirable silica per cubic meter of air ($mg/m^3$) as a time-weighted average (TWA) for up to a 10-hr day to reduce the risk of developing silicosis, lung cancer and other adverse health effects.(27) The ACGIH® threshold limit value (TLV®) for respirable silica (as $\alpha$ quartz) is 0.025 $mg/m^3$ TWA for up to an 8-hr workday.(28) The OSHA permissible exposure limit (PEL) for respirable dust containing silica in general industry is inversely weighted by the proportion of silica in the sampled dust and determined by the formula:$10 mg/m^3 \div (\%silica + 2)$.(29) For comparisons to the OSHA criterion, a PEL is calculated for each sample. Assuming 100% silica, the calculated PEL would be $\approx$0.10 $mg/m^3$ as an 8-hr TWA. NIOSH recommends minimizing risks for silica exposures to workers exposed at or above the REL by substituting less hazardous materials, using engineering controls to limit exposures, and, if engineering controls cannot control exposures $<$ REL, using respiratory protection and making medical examinations available to exposed workers.(23)

## METHODS

Exposure assessments for respirable crystalline silica were conducted for three consecutive days at 11 well sites in five states (Colorado, Texas, North Dakota, Arkansas, and Pennsylvania) from August 2010 through September 2011. Workers from 15 different job titles voluntarily participated. The purpose of the NIOSH field effort was explained to management and employees prior to sample collection; personal breathing zone (PBZ) samples were collected only on employees who agreed to participate. Workers participating on the first day were asked to participate on the two successive days of sampling, but sequential participation was not consistent at every site. After each day of sampling, NIOSH researchers discussed activities with employees and management to verify that samples were collected during typical hydraulic fracturing operations.

Full-shift (typically 12 hr) PBZ samples for respirable particulates and silica were simultaneously collected using AirChek XR 5000 (SKC Inc., Eighty Four, Pa.) personal sampling pumps connected to pre-weighed, 5-$\mu$m polyvinyl chloride filters in three-piece, 37-mm polystyrene sampling cassettes (Omega Specialty Division, SKC Inc.). The respirable fractions of dust were captured using BGI model GK2.69 cyclones (BGI Incorporated, Waltham, Mass.).(30) Sampling trains were calibrated in-line to the BGI recommended flow rate for respirable particulates at 4.2 L/min and post-calibrated with Dry Cal Defender 530 calibrators (Bios International, Butler Park, N.J.). Cyclones and cassettes were located in the worker's PBZ.

Kestrel model 4500 portable weather stations (Weather Republic, LLC, Downingtown, Pa.) were used to periodically measure temperature, relative humidity, and wind speed. Additional meteorological data were obtained from an on-line reporting service.

All samples were analyzed at an AIHA®-accredited laboratory, according to the *NIOSH Manual of Analytical Methods (NMAM)* method 0600, for gravimetric analysis of total particulates and NMAM method 7500, X-ray diffraction analysis for crystalline silica (as quartz, cristobalite, and tridymite).(31,32) For comparisons to the ACGIH TLV-TWA of 0.025 $mg/m^3$ and the NIOSH REL of 0.05 $mg/m^3$ as a TWA, calculations were made for the respirable fraction of silica alone. Numeric values reported by the laboratory for sample results between the limit of detection (LOD) and the limit of quantification (LOQ) were included in the statistical analysis of the data. If the respirable silica value was below the LOD, it was replaced by a value equal to the analytical LOD divided by the square root of 2, as described by Hornung and Reed.(33) Four samples for respirable quartz were below the LOD and included workers with job titles of Pump Truck Operator, QC Tech, and Wireline Operator.

To calculate TWA concentrations for the OSHA PEL for respirable dust containing $>1\%$ silica, percentage silica in the sample was determined by dividing the quartz results for each sample by amount of respirable dust and multiplying by 100. A PEL was calculated for each sample using the formula for general industry: $10 mg/m^3 \div (\%silica + 2)$.(29) PELs were not calculated for four samples where percentage quartz could not be determined because the respirable dust fraction was $<$ the LOD. Sample results are expressed for the full work shift (typically 12 hr); they were not adjusted for exposures exceeding the 8-hr OSHA or TLV criteria or the 8- to 10-hr REL.

Exposure severities were calculated by dividing the exposure TWA by the occupational exposure limit (PEL, REL) and expressed as a value greater or less than unity. Severities greater than unity exceed the respective exposure criterion. To compare and express the magnitude of work crew exposures in relation to a calculated PEL or REL, severity means, geometric means (GM), standard deviations, and minimum, maximum, and median values were calculated for the 15 job titles in units of $mg/m^3$.

A one-way analysis of variance was performed to evaluate for statistical differences in mean exposures among job titles with five or more samples (e.g., Blender Operators, Hydration Unit Operators, Sand Coordinators, Sand Mover Operators, T-belt Operators, and Water Tank Operators). Statistical differences between individual job title means were determined using the least significant difference (LSD) multiple comparison test (significance level, $p = 0.05$). The LSD can be seen as a t-test for differences between two means using a pooled error variance.(34) Analysis of variance and LSD statistical tests were also used for overall comparisons between the different work sites and for measured concentrations of respirable dust containing silica. All calculations were performed using SAS version 9.2 (SAS Institute Inc., Cary, N.C.).

## RESULTS

The 11 locations included geographic, topographic, climatic, altitude, and environmental diversity. Site locations included the Eagle Ford shale play in the southwest Texas desert during the summer. Two sites were in the temperate, humid deciduous forests of the Marcellus and Fayetteville shale plays of Pennsylvania and Arkansas in the spring. Seven well sites were on the arid high plains of the Denver-Julesburg (DJ) basin in Colorado in late winter and summer; one site was on the northern plains of the Bakken formation in North Dakota during late summer. Elevations ranged from approximately 300 feet to slightly more than 5000 feet above sea level.

The exposure assessments occurred at single- and multi-well site locations during single and multiple-stage completions. Typically, two or three stages were completed in a shift. The DJ Basin 1 sites in Colorado involved refracturing one zone of two different wells each day over three consecutive days, for a total of six different well locations. With the exception of the Bakken site where approximately 60% of the proppant was Black Cat (a ceramic material), silica sand was the proppant used at the other locations and included 20/40, 40/70, and 100 mesh sieve sizes. At some sites, a proportion of the total proppant load included resin-coated sand, but proportions, usage time, and volumes were not available.

### Weather

Meteorological conditions (average daily temperature and average daily low and high temperatures, sky conditions, precipitation, and wind speed) at the 11 sites are reported in Table I. Weather (wind, rain, or temperature) was never a limiting factor for site work. When it rained, rain was present for short periods, never interfering with sampling or completions operations. With exception of early to mid-morning periods, winds were typically measurable and varied, sometimes changing direction during the shift. Based on averages for the days the evaluations occurred, wind speed was in a range of 1.1–13 miles per hour (mph) at the sites. Average wind velocity and high wind was less (in a range of 1.1–5.4, and 10 mph, respectively) for the site on the Marcellus Shale in Pennsylvania.

### *Personal Breathing Zone Sampling Results*

Quartz was the only silicate mineral detected; the median value was 53% and samples ranged from < LOD to 100% quartz. Figure 1 describes silica concentrations in four discrete quantiles of 90th, 75th, 50th, and 25th percentiles. At the 90th percentile, 100 samples were determined to have up to 88% or less quartz.

Distribution of airborne particulates were evaluated and determined to follow a lognormal distribution using the Shapiro-Wilk test for goodness-of-fit and normality plots.[35,36] Logarithms of measured concentrations of respirable silica were used to calculate GM and standard deviations (SD) and for all statistical tests.

Table II lists 15 job titles, number of samples for each job title, the GM and geometric standard deviation (GSD) for respirable quartz in mg/m$^3$, and minimum, maximum, and median values expressed as TWAs. Geometric means and 95% confidence intervals for respirable silica concentrations for job titles having five or more samples are presented in Figure 2. Job titles with the highest GM exposures included T-belt and Sand Mover Operators (0.327 and 0.259); workers with lower GMs included Hydration Unit and Blender Operators (0.072 and 0.091); workers with the lowest GM exposures included Sand Coordinators and Water Tank Operators (0.054 and 0.048).

After exclusion of an obvious outlier for a T-belt Operator, no statistical differences were determined for exposures to respirable dust containing silica between Sand Mover Operators and T-belt Operators. Statistically significant differences ($p \leq 0.05$) were found between T-belt Operators compared with Sand Coordinators and Water Tank Operators and also between Sand Mover Operators and Hydration Unit Operators, Blender Operators, Sand Coordinators, and Water Tank Operators. For respirable silica alone, no statistical differences were found between Sand Mover Operators and T-belt Operators but significant differences ($p \leq 0.05$) were found between Sand Mover Operators and Hydration Unit Operators, Blender Operators, Sand Coordinators, and Water Tank Operators.

Table III lists the numbers and percentages of samples collected for each of the job titles that exceeded the ACGIH TLV, the NIOSH REL, or a calculated OSHA PEL. Figure 3 shows the comparisons for arithmetic means of respirable

**TABLE I. Meteorological Data at Six Shale Play Locations, 2010–2011**

| Location | Season | °F Avg. | °F Low | °F High | Sky | Precip. (inches) | Wind Speed Avg. Range (mph) | Wind Speed High (mph) |
|---|---|---|---|---|---|---|---|---|
| Eagle Ford, Texas | Summer | 87 | 75 | 101 | Clear | 0 | 8–11 | 14–15 |
| DJ Basin #1, Colo. | Winter | 49 | 38 | 71 | Clear-partly cloudy | 0 | 1.2–10 | 15–17 |
| Fayetteville, Ark. | Spring | 62 | 53 | 75 | Cloudy | 0.83 (0–1.5) | 7–10 | 11–12 |
| Marcellus, Pa. | Spring | 74 | 63 | 92 | Cloudy-partly cloudy | 0.22 | 1.1–5.4 | 10 |
| DJ Basin #2, Colo. | Summer | 70 | 58 | 91 | Clear-partly cloudy | 0.05 | 10–13 | 15–16 |
| Bakken, N.D. | Summer | 68 | 56 | 89 | Clear-partly cloudy | 0.22–0.5 | 7–12 | 11–35 |

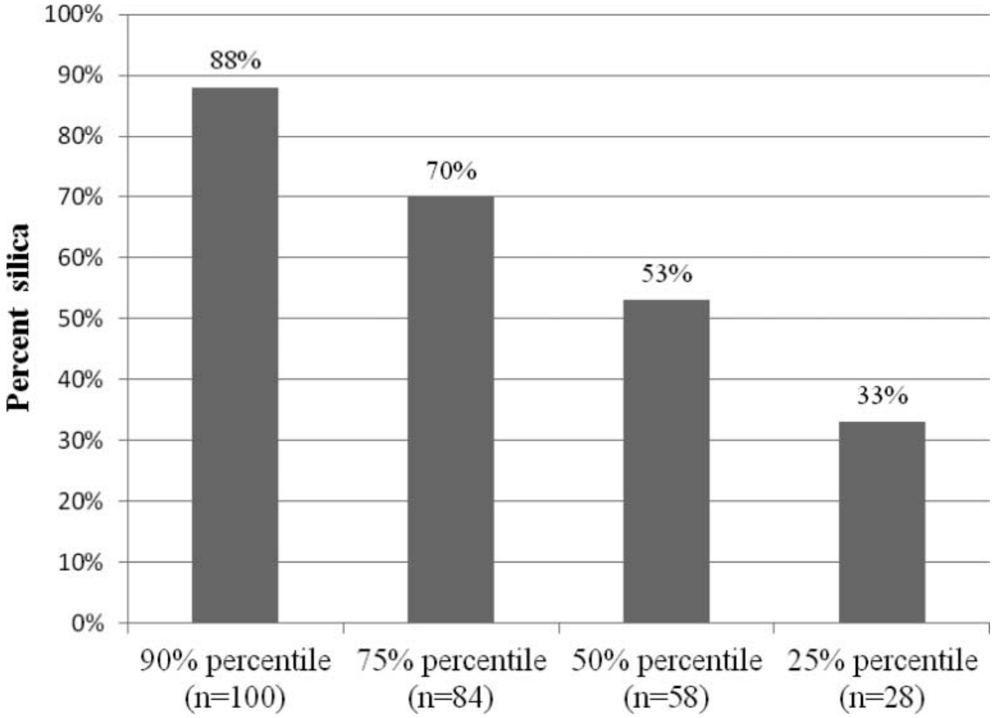

**FIGURE 1.** Quantiles, distribution of percent silica in PBZ samples (n = 111).

silica TWAs (mg/m$^3$) for job titles with five or more samples and a calculated OSHA PEL used for comparison purposes in this figure based the median value of 53% silica content in the 111 samples, and the NIOSH REL value.

To compare and express the magnitude of work crew exposures in relation to OSHA PELs for respirable dust containing silica and the NIOSH REL for respirable silica alone, means of job title severities were calculated and are listed in Tables IV and V for the NIOSH REL or the OSHA PEL, respectively. Arithmetic standard deviations (ASD), minimum, maximum, and median values are also listed as these can be used for direct comparisons to occupational exposure criteria (PEL, REL and

**TABLE II. PBZ Statistics by Job Title, Respirable Quartz TWA (mg/m$^3$)**

| Job Title | No. of Samples | GM | GSD | Min TWA | Max TWA | Median TWA |
|---|---|---|---|---|---|---|
| Blender Operator | 16 | 0.091 | 1.266 | 0.007 | 0.485 | 0.102 |
| Chemical Truck Operator | 3 | 0.121 | 1.828 | 0.040 | 0.319 | 0.139 |
| Fueler | 2 | 0.042 | 1.225 | 0.034 | 0.051 | 0.043 |
| Hydration Unit Operator | 5 | 0.072 | 2.209 | 0.009 | 0.746 | 0.044 |
| Mechanic | 3 | 0.052 | 1.511 | 0.023 | 0.088 | 0.069 |
| Operator, Data Van | 1 | 0.043 | — | 0.043 | 0.043 | 0.043 |
| Pump Truck Operator | 1 | 0.021 | — | 0.021 | 0.021 | 0.021 |
| QC Tech | 1 | 0.013 | — | 0.013 | 0.013 | 0.013 |
| Roving Operator | 4 | 0.019 | 1.628 | 0.006 | 0.059 | 0.020 |
| Sand Coordinator | 10 | 0.054 | 1.333 | 0.017 | 0.326 | 0.061 |
| Sand Truck Driver | 1 | 0.041 | — | 0.041 | 0.041 | 0.041 |
| Sand Mover Operator | 50 | 0.259 | 1.223 | 0.007 | 2.755 | 0.381 |
| T-belt Operator | 6 | 0.327 | 2.003 | 0.015 | 2.570 | 0.453 |
| Water Tank Operator | 7 | 0.048 | 1.339 | 0.019 | 0.136 | 0.056 |
| Wireline Operator | 1 | 0.007 | — | 0.007 | 0.007 | 0.007 |
| Totals | 111 | 0.122 | 1.152 | 0.006 | 2.755 | 0.109 |

*Notes:* Titles followed by superscripts are significantly different ($p \leq 0.05$). Values not calculated for statistics where N = 1.

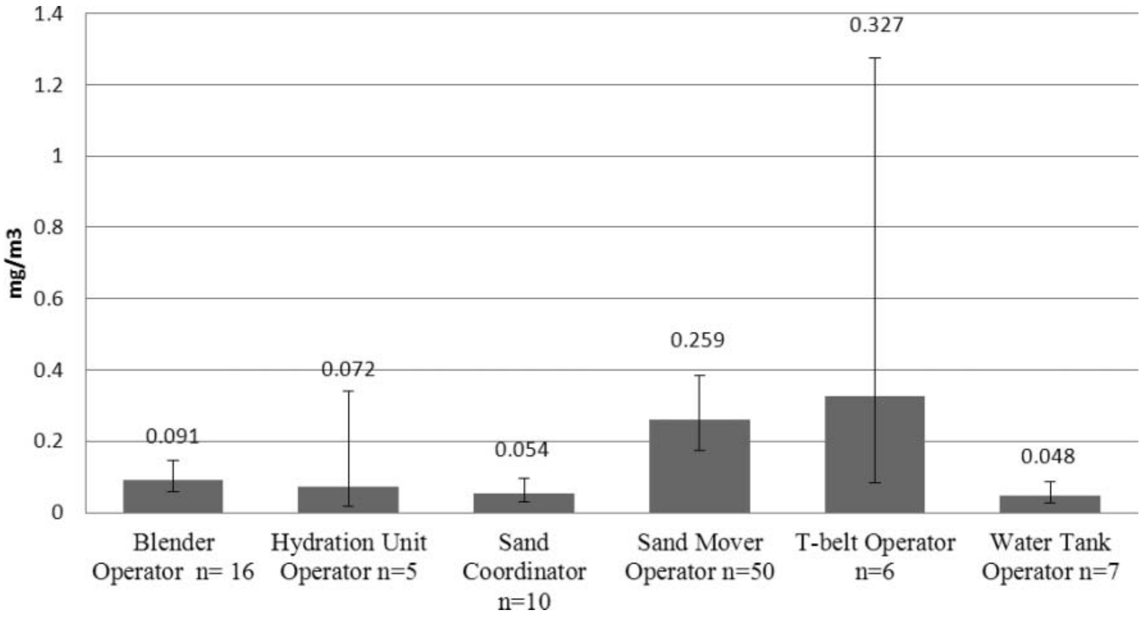

**FIGURE 2**. Respirable silica geometric means (mg/m$^3$) and 95% confidence intervals for job titles with 5 or more samples

TLV). Job titles with the highest mean severities included Transfer Belt and Sand Mover Operators (mean severities of 14.55 and 10.44, respectively, based on the NIOSH REL). Job titles with lowest exposures (mean severities less than one, and for samples where $n > 1$) included Roving Operator (0.52) and Fueler (0.85) who worked in a variety of locations at the sites or spent only short periods of time in site areas when sand was being transported on site. Job titles with exposures greater than 10 times the NIOSH REL included Sand Mover Operator ($n = 19$), Transfer Belt Operator ($n = 2$), and Hydration Unit Operator ($n = 1$).

### *Personal Breathing Zone Respirable Silica by Job Site*

Statistically significant differences ($p \leq 0.05$) in overall concentrations of respirable silica were not found between the Eagle Ford, Fayetteville shale, DJ Basin 1 and 2 sites, and Marcellus shale formations; however, all these sites (except the Eagle Ford) did differ from the Bakken formation where ceramic was the primary proppant used at that site.

Table VI lists the sites, numbers of samples collected, and percentages that exceeded the TLV, REL, or the calculated PELs. Ninety three of 111 (83.8%) of the samples exceeded the TLV, 76 (68.5%) exceeded the REL, and 57

**TABLE III. Samples Above ACGIH TLV, NIOSH REL, or OSHA PEL**

| Job Title | ACGIH TLV | NIOSH REL | OSHA PEL | No. of Samples |
|---|---|---|---|---|
| Blender Operator | 15 (93.8%) | 13 (81.3%) | 8 (50%) | 16 |
| Chemical Truck Operator | 3 (100%) | 2 (66.7%) | 2 (66.7%) | 3 |
| Fueler | 2 (100%) | 0 | 0 | 2 |
| Hydration Unit Operator | 4 (80%) | 2 (40%) | 2 (40%) | 5 |
| Mechanic | 2 (66.7%) | 2 (66.7%) | 0 | 3 |
| Operator, Data Van | 1 (100%) | 0 | 0 | 1 |
| Pump Truck Operator | 0 | 0 | 0 | 1 |
| QC Tech | 0 | 0 | 0 | 1 |
| Roving Operator | 2 (50%) | 1 (25%) | 0 | 4 |
| Sand Coordinator | 7 (70%) | 5 (50%) | 1 (10%) | 10 |
| Sand Truck Driver | 1 (100%) | 0 | 0 | 1 |
| Sand Mover Operator | 46 (92%) | 42 (84%) | 37 (74%) | 50 |
| T-belt Operator | 5 (83.3%) | 5 (83.3%) | 5 (83.3%) | 6 |
| Water Tank Operator | 5 (71.7%) | 4 (57.1%) | 2 (28.6%) | 7 |
| Wireline Operator | 0 | 0 | 0 | 1 |
| Totals | 93 (83.8%) | 76 (68.5%) | 57 (51.4%) | 111 |

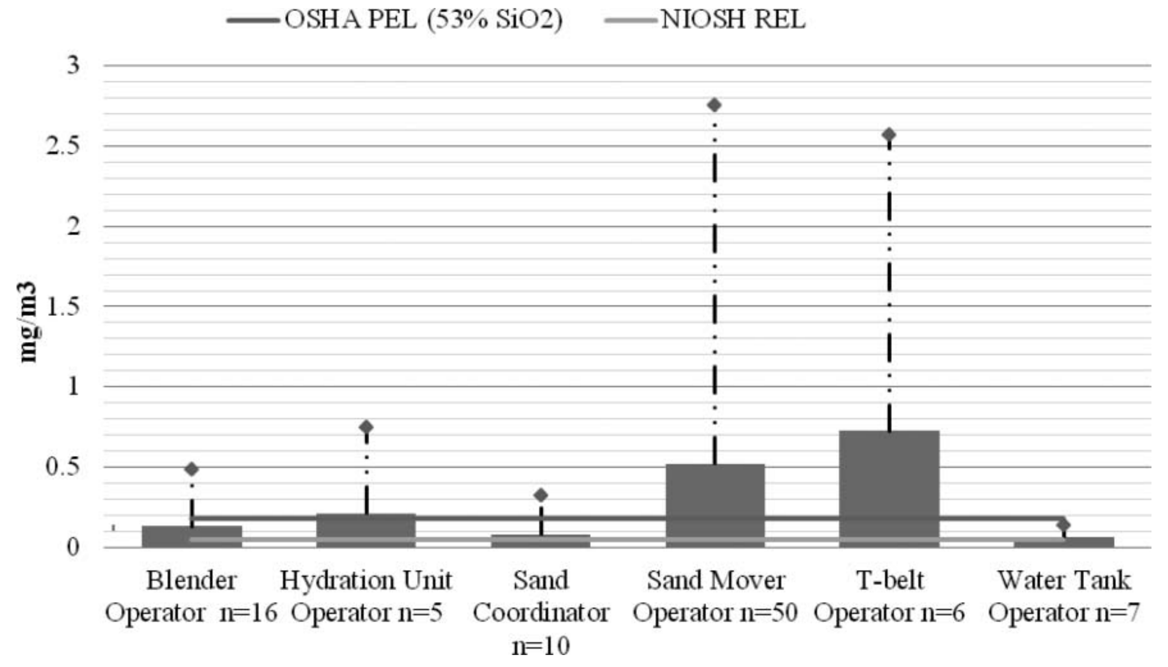

**FIGURE 3**. Comparisons of arithmetic means of TWAs (mg/m$^3$) for job titles with five or more samples in relation to a calculated OSHA PEL (based on 53% silica) and NIOSH REL for respirable silica. Maximum values for each job title shown by diamonds at the end of dashed lines.

(51.4%) exceeded a calculated PEL for respirable dust containing silica.

### *Magnitude of Full-Shift Exposures to Respirable Crystalline Silica*

Silica exposures for some job titles exceeded the assigned protection factor of 10 for the half-mask, air-purifying respirators most commonly used at the locations. PBZ exposures exceeding a REL or PEL by a factor of 10 or more included Sand Mover Operators, n = 19 for the REL, n = 8 for the OSHA PEL, and T-belt Operators, and n = 2 and 1 for the REL and PEL, respectively. In some cases, exposures exceeded OELs by a factor greater than 20, including Sand Mover Operator (n = 7) and T-belt Operators (n = 1) for the

**TABLE IV. PBZ NIOSH REL Mean Severities**

| Job Title | No. of Samples | AM | ASD | Min | Max | Median |
|---|---|---|---|---|---|---|
| Blender Operator | 16 | 2.58 | 0.59 | 0.14 | 9.70 | 2.03 |
| Chemical Truck Operator | 3 | 3.32 | 1.63 | 0.80 | 6.38 | 2.78 |
| Fueler | 2 | 0.85 | 0.17 | 0.68 | 1.02 | 0.85 |
| Hydration Unit Operator | 5 | 4.28 | 2.79 | 0.18 | 14.92 | 0.88 |
| Mechanic | 3 | 1.20 | 0.39 | 0.46 | 1.76 | 1.38 |
| Operator, Data Van | 1 | 0.86 | — | 0.86 | 0.86 | 0.86 |
| Pump Truck Operator | 1 | 0.42 | — | 0.42 | 0.42 | 0.42 |
| QC Tech | 1 | 0.26 | — | 0.26 | 0.26 | 0.26 |
| Roving Operator | 4 | 0.52 | 0.24 | 0.12 | 1.18 | 0.39 |
| Sand Coordinator | 10 | 1.60 | 0.57 | 0.34 | 6.52 | 1.22 |
| Sand Truck Driver | 1 | 0.82 | — | 0.82 | 0.82 | 0.82 |
| Sand Mover Operator | 50 | 10.44 | 1.59 | 0.14 | 55.10 | 7.62 |
| T-belt Operator | 6 | 14.55 | 7.57 | 0.30 | 51.40 | 9.06 |
| Water Tank Operator | 7 | 1.23 | 0.34 | 0.38 | 2.72 | 1.12 |
| Wireline Operator | 1 | 0.14 | — | 0.14 | 0.14 | 0.14 |
| Totals | 111 | 6.45 | 0.93 | 0.12 | 55.10 | 2.18 |

*Note:* Values not calculated for samples where n = 1.

TABLE V. PBZ OSHA PEL Mean Severities

| Job Title | No. of Samples | AM | ASD | Min | Max | Median |
|---|---|---|---|---|---|---|
| Blender Operator | 16 | 1.34 | 0.30 | 0.09 | 4.93 | 1.08 |
| Chemical Truck Operator | 3 | 1.70 | 0.82 | 0.45 | 3.23 | 1.41 |
| Fueler | 1 | 0.57 | — | 0.57 | 0.57 | 0.57 |
| Hydration Unit Operator | 5 | 2.19 | 1.42 | 0.09 | 7.58 | 0.4 |
| Mechanic | 3 | 0.61 | 0.20 | 0.23 | 0.90 | 0.70 |
| Operator, Data Van | 1 | 0.49 | — | 0.49 | 0.49 | 0.49 |
| Pump Truck Operator | 0 |  |  |  |  |  |
| QC Tech | 1 | 0.14 | — | 0.14 | 0.14 | 0.14 |
| Roving Operator | 4 | 0.25 | 0.09 | 0.08 | 0.50 | 0.21 |
| Sand Coordinator | 10 | 0.81 | 0.27 | 0.18 | 3.10 | 0.65 |
| Sand Truck Driver | 1 | 0.41 | — | 0.41 | 0.41 | 0.41 |
| Sand Mover Operator | 50 | 5.66 | 0.86 | 0.13 | 28.71 | 4.26 |
| T-belt Operator | 6 | 7.62 | 4.05 | 0.18 | 27.39 | 4.65 |
| Water Tank Operator | 7 | 0.63 | 0.17 | 0.21 | 1.36 | 0.54 |
| Wireline Operator | 1 | 0.07 | — | 0.07 | 0.07 | 0.07 |

*Note:* Values not calculated for samples where n = 1.

NIOSH REL, and n = 3 and n = 1 for the same job titles for the OSHA calculated PEL. If the sampling results were adjusted for an extended work shift, that is, the difference between an 8-hr shift and a 12-hr work shift, the exposure severities would be 50% greater than those listed and described.

## DISCUSSION

### Sources of Silica-Containing Dust Identified at the Work Sites

Dust is visibly present during hydraulic fracturing especially when sand movers are refilled and actively operating, which is referred to as "hot loading." Workers closest to sand moving operations included T-belt and Sand Mover Operators (Figure 2), followed by Blender and Hydration Unit Operators. Direction and wind speed, as well as the configuration of the sand handling and other equipment on site, appear to influence the concentration, direction, and migration of airborne sand dusts. Predictably, when workers were near or downwind from point sources of dust generation they had greater risks for exposures than if farther away or upwind. At some sites, how equipment was configured and positioned created enclosed or restricted environments that may have limited natural dilution of airborne particulates and contributed to increased exposures to airborne dusts.

Workers less commonly observed in the immediate area of sand moving machinery included Sand Coordinators (Ground Guides), Water Tank Operators, and Chemical Truck Operators. However, in some cases, these job titles had exposures > TLV, REL, or the PEL, indicating that PBZ exposures exceeding these concentrations can occur even when workers were not in proximity to the primary source(s) of dust generation. This could be due to silica-containing environmental dust carried onto the site or dusts generated from on-site vehicular traffic.

Blender, Chemical Truck, and Hydration Unit Operators worked in both closed and open cabs on their machinery, and these job titles had exposures that exceeded OELs even when Operators reported or were observed to spend most of the day in a cab. Blender trucks typically had enclosed cabs, but none had high-efficiency particulate filtration or positive pressurization. Respirable silica concentrations for workers in

TABLE VI. Samples Above ACGIH TLV, NIOSH REL, or OSHA PEL

| Site | ACGIH TLV | NIOSH REL | OSHA PEL | Total No. Samples |
|---|---|---|---|---|
| Fayetteville, Ark. | 24 (92.3%) | 19 (73.1%) | 14 (53.9%) | 26 |
| DJ Basin 1, Colo. | 16 (84.2%) | 14 (73.7%) | 12 (63.2%) | 19 |
| Eagle Ford, Texas | 5 (62.5%) | 5 (62.5%) | 4 (50.0%) | 8 |
| DJ Basin 2, Colo. | 19 (90.5%) | 14 (66.7%) | 9 (42.9%) | 21 |
| Marcellus, Pa. | 25 (92.6%) | 23 (85.2%) | 18 (66.7%) | 27 |
| Bakken, N.D. | 4 (40%) | 1 (10%) | 0 | 10 |
| Totals | 93 (83.8%) | 76 (68.5%) | 57 (51.4%) | 111 |

vehicles having doors with tight-fitting seals and conditioned environments (e.g., data vans) did not exceed the TLV, REL, or PELs, with the exception of one Operator who spent time near sand moving equipment for a portion of the day.

Seven points of dust generation were consistent at each of the 11 work sites:

(1) Dust ejected from "thief hatches" on the tops of sand movers during filling. This source contributes to exposures to Sand Mover and Blender Operators and, depending on winds, may expose workers farther away, such as Water Tank Operators.
(2) Dusts released from the sand mover belt. This point source was observed to contribute to exposures to Sand Mover Operators, especially if the wind is strong and the Operator station is on the downwind side of the machine.
(3) Dust created at the blender hopper from the momentum of falling proppant below the dragon tail can contribute to exposure to Sand Mover and Blender Operators; the area below the dragon tail can be confined due to interacting machinery (Blender, Sand Movers, the T-belt), and depending on climatic conditions, there could also be a lack of natural ventilation.
(4) Dust released from T-belts when proppant is deposited onto the belt and conveyed to the blender. Sand impacting the belt as well as rotational and vibrational movement of the belt contributes to dust generation.
(5) Dust generated as proppant leaves the end of the dragon tail. This can be a secondary contributing source for both Blender Operators (i.e., cab-based operator and the hopper-based operator or other downwind work crews).
(6) Dust ejected from fill ports of sand movers during refilling operations. An absence of caps on the fill ports contributes to silica exposures of Sand Mover Operators, Blender Operators, and Sand Truck Drivers.
(7) Dust generated by site traffic, including frictional forces from truck tires, vehicle momentum, and release of air pressure from pneumatic brakes, contributes to exposures to Sand Coordinators and Sand Truck Drivers. Dust blown onto the work site from off-site sources was also observed on several occasions and may be a small and variable contributor to work crew exposures.

## CONCLUSION

Full-shift, PBZ exposures to respirable crystalline silica is an occupational exposure hazard for workers at hydraulic fracturing sites. Quartz was the only silicate mineral identified; median percentage quartz in the 111 PBZ samples was 53%. Workplace concentrations of airborne respirable silica exceeded OELs by factors of 10, 20, or more, with Sand Mover and Transfer Belt Operators having the highest relative exposures. Although workers typically wore elastomeric half-mask, air-purifying (or filtering-facepiece style) respirators, due to the magnitude of the silica concentrations measured, half-masks may not be sufficiently protective because, in some cases, respirable crystalline silica concentrations exceeded the maximum use concentration (10 times the OEL) for that type of respirator.

Although effective engineering controls for crystalline silica are well established in other industries, controls to limit silica-containing dust generation during hydraulic fracturing are only now emerging due to the relatively recent understanding of the hazard and magnitude of exposure risks. Sand movers configured with some proposed controls (e.g., a mini-baghouse retrofit assembly, skirting and shrouding at the base of the machine and on the dragon tail, and use of caps on fill ports) are described in Figures 1 and 2 in the online supplemental material discussing controls and recommendations. At one site (Bakken formation in North Dakota) substitution of a ceramic proppant for a portion of silica sand resulted in lower overall measured silica exposures, but assessing the technical and economic feasibility of using ceramic proppant was beyond the scope of this study.

## ACKNOWLEDGMENTS

We gratefully thank the oil and gas operators and completions companies—and especially their employees—for their demonstrated leadership in occupational health and safety by agreeing to participate in the NIOSH Field Effort to Assess Chemical Exposures in Oil and Gas Workers. We extend our deep gratitude to Rick Ingram (BP, Houston, Texas, and the National Service, Transmission, Exploration & Production Safety [STEPS] Network) for his encouragement and support of the NIOSH Field Effort and his determined efforts organizing and moderating the 2012 Respirable Silica Focus Group, a recently organized effort involving the oil and gas industry, other related industries, NIOSH, and OSHA in collective discussions and actions toward rapid development and implementation of engineering, administrative, and personal protective equipment controls to increase awareness and protect completions crews from crystalline silica exposures.

In addition, we thank Kenneth Strunk, NIOSH Office of Mining Health and Safety Research, Spokane, Washington, for development of computer renderings of the NIOSH mini-bag house assembly and other controls; and Corey Campbell of the NIOSH Western States Office for her assistance with graphics.

We expressly recognize and thank Alan Echt, NIOSH Division of Applied Research and Technology; Jim Helmkamp of the NIOSH Western States Office; Dan Sharp of the NIOSH Health Effects Laboratory Division, Morgantown, West Virginia (detailed to NIOSH Western States Office); and Aaron Sussell, NIOSH, Division of Surveillance, Hazard Evaluations and Field Studies, for their reviews and thoughtful comments on preliminary drafts of the manuscript.

## DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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On Thursday, November 21, 2013 11:05 AM, USGS Newsroom <oc_web@usgs.gov> wrote:

# Measuring Landscape Disturbance of Gas Exploration in Four More Pennsylvania Counties:

## Measuring Landscape Disturbance of Gas Exploration in Four More Pennsylvania Counties:

Posted: 21 Nov 2013 06:23 AM PST

### *Sullivan, Wyoming, Armstrong and Indiana Counties Examined*

Landscape change in Pennsylvania's Sullivan, Wyoming, Armstrong and Indiana counties resulting from construction of well pads, new roads and pipelines for natural gas and coalbed methane exploration is being documented to help determine the potential consequences for ecosystems and wildlife, according to two U.S. Geological Survey reports released today.

Using geospatial data and high resolution aerial imagery from 2004-2010, USGS researchers documented spatially explicit patterns of disturbance, or land use, related to natural gas resource development, such as hydraulic fracturing, particularly disturbance patterns related to well pads, roads and pipeline construction.

Researchers found that in Sullivan County, 8 natural gas extraction sites resulted in more than 24 hectares of disturbance, including 2.4 kilometers (1.49 miles) of new roads and no new pipelines. In Sullivan County, disturbance is sparsely distributed along the northern edge of the county. Most of this disturbance is Marcellus related.

In Wyoming County, 22 natural gas extraction sites resulted in more than 59 hectares of disturbance, including 4.5 kilometers (2.79 miles) of new roads and 2.2 kilometers (1.36 miles) of new pipelines. In Wyoming County, disturbance is dispersed in the northwest quadrant of the county and is related to Marcellus Shale natural gas extraction.

The study found that in Armstrong County, 1,912 natural gas extraction sites resulted in more than 1376 hectares of disturbance, including 515.6

kilometers (320.37 miles) of new roads and more than 63.3 kilometers (39.33 miles) of new pipelines.

In Indiana County, 1,875 natural gas extraction sites resulted in more than 1,493 hectares of disturbance, including more than 572.1 kilometers (355.48 miles) of new roads and 71.3 kilometers (44.30 miles) of new pipelines.

Spatially explicit data on the level of landscape disturbance -- which is geographic information systems data, mapped to a high degree of spatial accuracy -- is critically important to the long-term study of the potential impacts of natural gas development on human and ecological health.

Through programs such as the National Land Cover Database, and Land Cover Trends, USGS has a long record of studying the consequences of land-use and land-cover changes. The current level of natural gas development in much of the country, and its effects on the landscape, is an important contemporary land-use/land-cover issue.

"These studies are part of the larger USGS evaluation of disturbance due to natural gas extraction in the Marcellus Shale region of Pennsylvania. They show the level of activity in these four counties and will help create a total picture of the level of landscape disturbance in the region in 2010," said Terry Slonecker, project lead.

With the release of information on the four counties today, the USGS has completed analysis of landscape disturbance in 18 Pennsylvania counties. Results of studies on 17 more counties in the state will be released in the coming months.

Data from these reports will be used to assess the effects of disturbance and land-cover change on wildlife, water quality, invasive species and socioeconomic impacts, among other investigations.

The study, "**Landscape consequences of natural gas extraction in Sullivan and Wyoming Counties, Pennsylvania, 2004-2010**," by, E.T. Slonecker, L.E. Milheim, C.M. Roig-Silva, and A.R. Malizia Open File Report 2013-1261 and “**Landscape consequences of natural gas extraction in Armstrong and Indiana Counties, Pennsylvania, 2004-2010**," by, L.E. Milheim, E.T. Slonecker, C.M. Roig-Silva, and A.R. Malizia Open File Report 2013-1263 are part of a series relating to natural gas landscape disturbance and are available online.

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# Landscape Consequences of Natural Gas Extraction in Allegheny and Susquehanna Counties, Pennsylvania, 2004–2010

By E.T. Slonecker, L.E. Milheim, C.M. Roig-Silva, and A.R. Malizia

Open-File Report 2013–1025

**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
KEN SALAZAR, Secretary

**U.S. Geological Survey**
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

Suggested citation:
Slonecker, E.T., Milheim, L.E., Roig-Silva, C.M., and Malizia, A.R., 2013, Landscape consequences of natural gas extraction in Allegheny and Susquehanna Counties, Pennsylvania, 2004–2010: U.S. Geological Survey Open-File Report 2013–1025, 34 p., http://pubs.usgs.gov/of/2013/1025.

## Contents

## Figures

## Tables

# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 4,047 | square meter (m2) |
| acre | 0.4047 | hectare (ha) |

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Area | |
| square meter (m2) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

# Landscape Consequences of Natural Gas Extraction in Allegheny and Susquehanna Counties, Pennsylvania, 2004–2010

By E.T. Slonecker, L.E. Milheim, C.M. Roig-Silva, and A.R. Malizia

## Abstract

Increased demands for cleaner burning energy, coupled with the relatively recent technological advances in accessing unconventional hydrocarbon-rich geologic formations, have led to an intense effort to find and extract natural gas from various underground sources around the country. One of these sources, the Marcellus Shale, located in the Allegheny Plateau, is currently undergoing extensive drilling and production. The technology used to extract gas in the Marcellus Shale is known as hydraulic fracturing and has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on water resources. Nonetheless, development of natural gas extraction wells in the Marcellus Shale is only part of the overall natural gas story in this area of Pennsylvania. Coalbed methane, which is sometimes extracted using the same technique, is commonly located in the same general area as the Marcellus Shale and is frequently developed in clusters of wells across the landscape. The combined effects of these two natural gas extraction methods create potentially serious patterns of disturbance on the landscape. This document quantifies the landscape changes and consequences of natural gas extraction for Allegheny County and Susquehanna County in Pennsylvania between 2004 and 2010. Patterns of landscape disturbance related to natural gas extraction activities were collected and digitized using National Agriculture Imagery Program (NAIP) imagery for 2004, 2005/2006, 2008, and 2010. The disturbance patterns were then used to measure changes in land cover and land use using the National Land Cover Database (NLCD) of 2001. A series of landscape metrics is also used to quantify these changes and is included in this publication.

## Introduction: Natural Gas Extraction

The need for cleaner burning energy, coupled with the relatively recent technological advances in accessing hydrocarbon-rich geologic formations, has led to an intense effort to find and extract natural gas from various underground sources around the country. One of these formations, the Marcellus Shale, is currently the target of extensive drilling and production in the Allegheny Plateau. Marcellus Shale generally extends from New York to West Virginia, as shown in figure 1 (Coleman and others, 2011). Coleman and others (2011) defined assessment units (AU) of Marcellus Shale production based on the geology of the region.

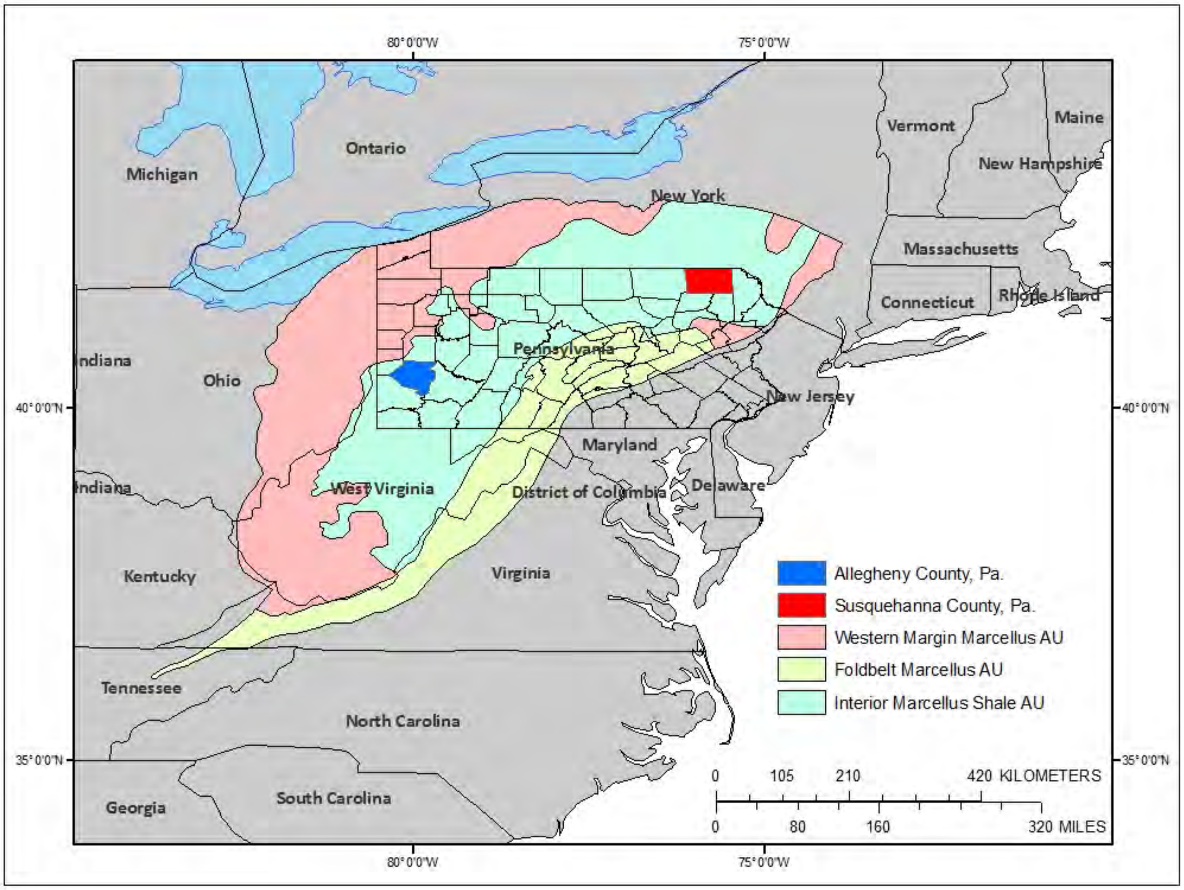

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus Shale AU is expected to be a major production area for natural gas (Coleman and others, 2011). Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

The overall landscape effects of natural gas development have been considerable. Over 9,600 Marcellus Shale gas drilling permits and over 49,500 non-Marcellus Shale permits have been issued from 2000 to 2011 in Pennsylvania (Pennsylvania Department of Environmental Protection, 2011), and over 2,300 Marcellus Shale permits have been issued in West Virginia (West Virginia Geological and Economic Survey, 2011), with most of the development activity occurring since 2005.

The Marcellus Shale is generally located 600 to 3,000 meters (m) below the land surface (Coleman and others, 2011). Gas and petroleum liquids are produced using a combination of vertical and horizontal drilling techniques, coupled with a process of hydraulically fracturing the shale formation, known as "fracking," which releases the natural gas.

The hydraulic-fracturing process has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on groundwater and drinking-water resources.

However, with all of the development of natural gas wells in the Marcellus Shale, it is only part of the overall natural gas story in this area. Coalbed methane, which is extracted in similar ways, is commonly located in the same general area as the Marcellus Shale. The coalbed methane wells are much shallower and less productive and are often located in clusters that cover large areas of the landscape, with nearly 60,000 total gas wells established. Both types of wells may affect a given area. With the accompanying areas of disturbance, well pads, new roads, and pipelines from both types of natural gas wells, the effect on the landscape is often dramatic. Figure 2 shows an example of a pattern of landscape change from forest to forest interspersed with gas extraction infrastructure. These landscape effects have consequences for the ecosystems, wildlife, and human populations that are co-located with natural gas extraction activities. This document examines the landscape consequences of gas extraction for two areas of current Marcellus Shale and non-Marcellus Shale natural gas extraction activity.

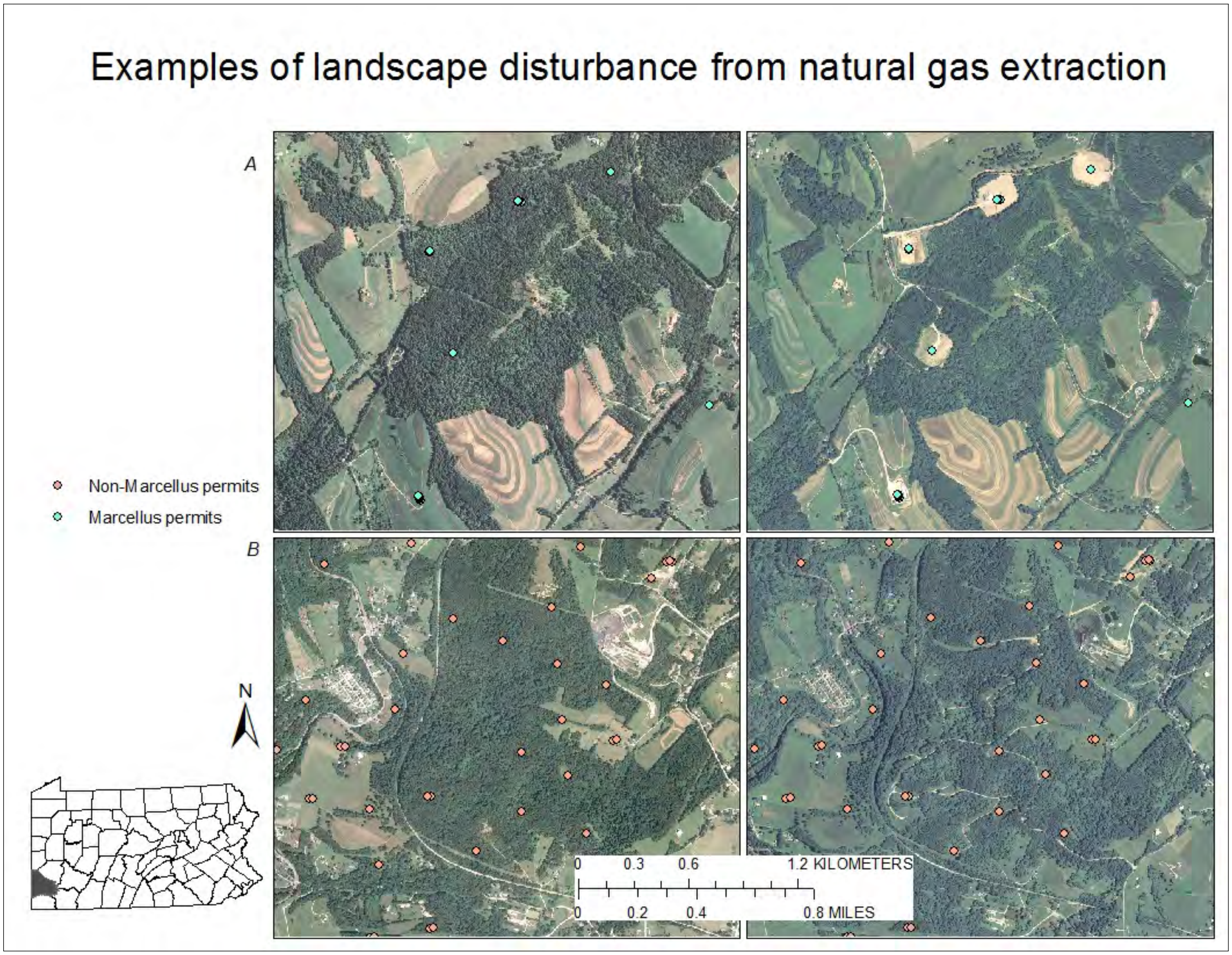

**Figure 2.** Examples of forested landscapes from Washington County, Pennsylvania, showing the spatial effects of roads, well pads, and pipelines related to (*A*) Marcellus Shale and (*B*) Conventional natural gas development. Left-hand side shows areas prior to development; right-hand side shows areas after development. Inset shows the location of the images. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer)* (*U.S.* Geological Survey, 2011a)].

## Location

This assessment of landscape effects focuses on two counties, Allegheny County and Susquehanna County in Pennsylvania, within the Marcellus Shale area of development known as the “Marcellus Shale Play,” or the Interior Marcellus Shale AU. These counties were chosen for their position within the “sweet spots” of exceptionally productive Marcellus Shale within the Interior Marcellus Shale AU (Stevens and Kuuskraa, 2009). Figure 3 identifies the selected counties in relation to the Interior Marcellus Shale AU and the distribution of Marcellus and non-Marcellus gas extraction permits granted by Pennsylvania from 2004 to 2010.

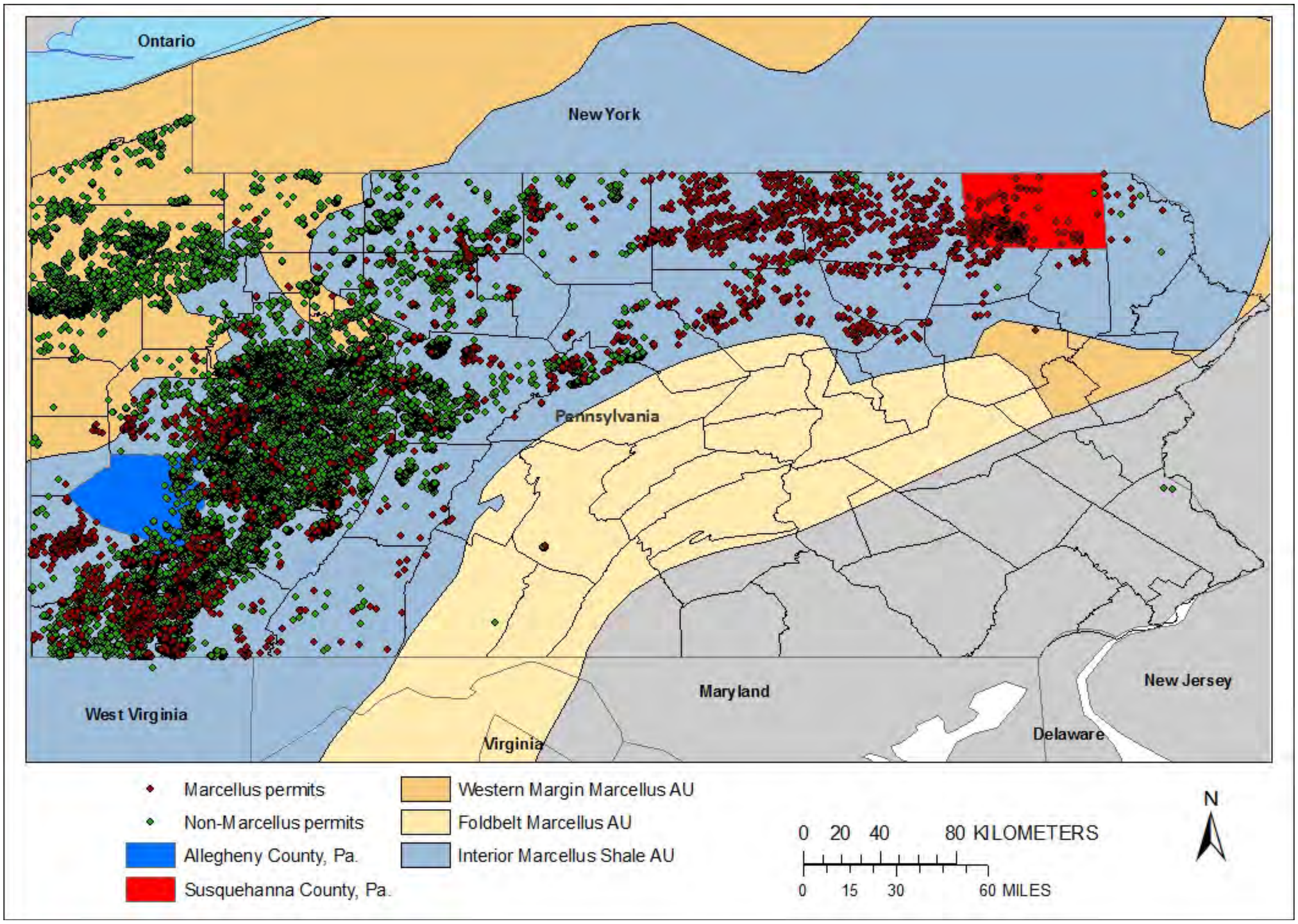

**Figure 3.** The distribution of Marcellus and non-Marcellus natural gas permits issued between 2004 and 2010 within Pennsylvania, the focal counties of Allegheny and Susquehanna, and their relation to the Interior Marcellus Shale assessment unit. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

## The Biogeography of Pennsylvania Forests

Forests are a critical land cover in Pennsylvania. Prior to the European settlements, Pennsylvania was almost completely forested and even today, with modern agriculture, urban growth, and population growth, Pennsylvania is still roughly 60 percent forested. Pennsylvania forests of the 17th century were diverse but were dominated by beech and hemlock, which composed 65 percent of the total forest

(Pennsylvania Department of Conservation and Natural Resources, 2011). However, in the late 19th century, Pennsylvania became the country's leading source of lumber, and a number of products, from lumber to the production of tannic acid, were generated from the forestry industry (Pennsylvania Department of Conservation and Natural Resources, 2011). By the early 20th century, most of Pennsylvania's forests had been harvested. Soon after most of the trees were felled, wildfires, erosion, and flooding became prevalent, especially in the Allegheny Plateau region (Pennsylvania Parks and Forests Foundation, 2010).

The 20th century saw a resurgence in Pennsylvania forests. The Weeks Act of 1911 authorized the Federal purchase of forest land on the headwaters of navigable rivers to control the flow of water downstream and act as a measure of flood control for the thriving steel industry of Pittsburgh. Slowly, the forests began to grow back but with a vastly different composition, this time composed of black cherry, red maple, and sugar maple species (Pennsylvania Parks and Forests Foundation, 2010). For the most part, except for a very few isolated areas in north-central Pennsylvania and some State parks, the majority of forest cover is currently of the new composition and not of virgin forest. Figure 4 shows that today the concentrations of forests in Pennsylvania are highest in the central and north-central parts of the State, which is also the main area of hydraulic-fracturing activity in the Marcellus Shale.

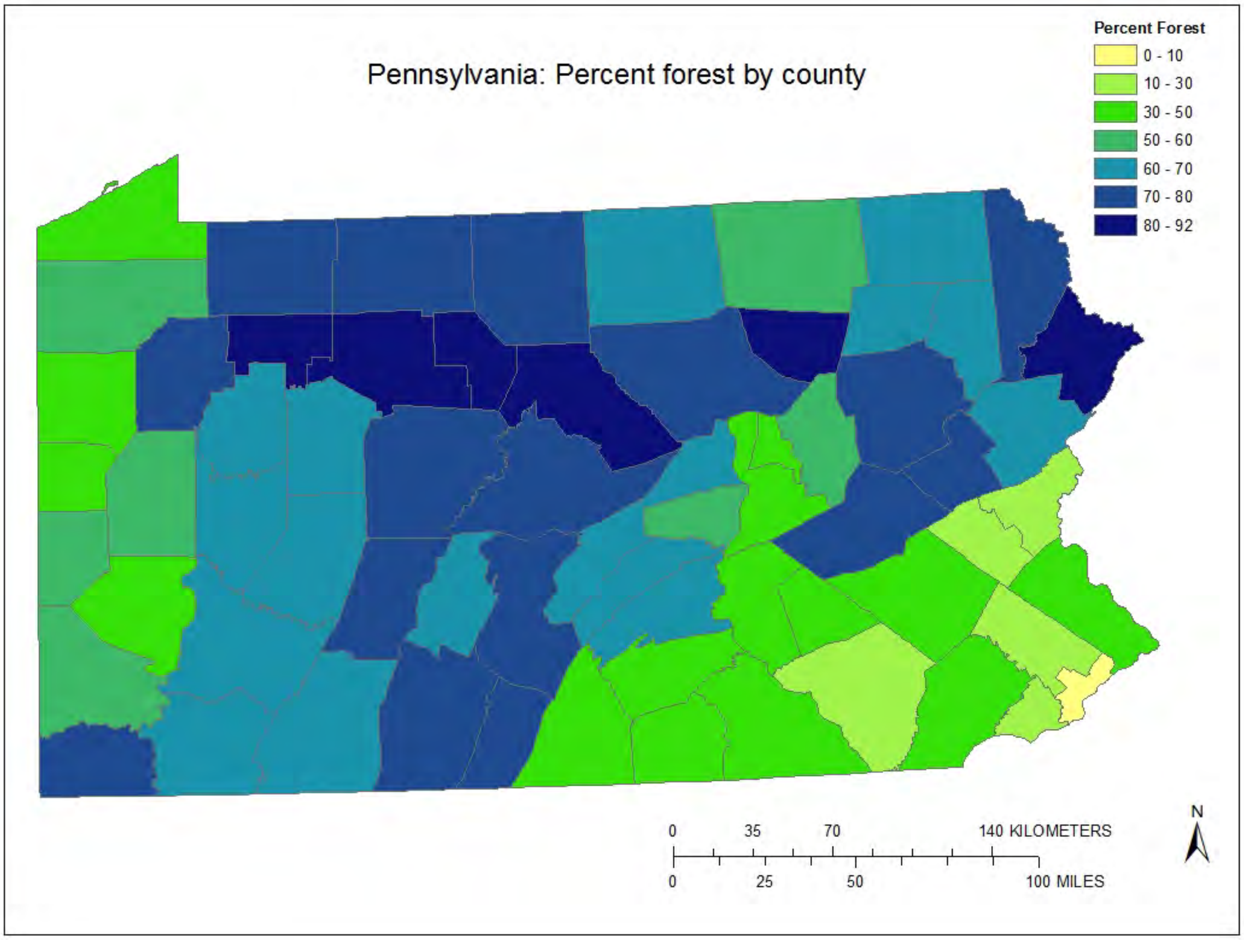

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Database. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (*U.S.* Geological Survey, 2011a)].

Pennsylvania forests provide critical habitat to a number of plant and animal species. Plant species include the sugar maple, the eastern redcedar, and evergreens that produce berries in the winter. There were a number of animal species that have been eradicated from the region, such as elk, moose, North American cougar, bison, and grey wolf (Nilsson, 2005). Today, animal species range from the more commonly found animals such as skunks to flying squirrels, and multiple different varieties of snakes and bats. However, a diverse population of birds depends on the forests for survival. In the State of Pennsylvania; there are 394 different bird species that are native, including endangered species such as the piping plover (Gross, 2005).

### Key Research Questions

An important aspect of this research is to quantify the level of disturbance in terms of land use and land cover change by specific disturbance category (well pads, roads, pipelines, and so forth). This quantification will be accomplished by extracting the signatures of disturbance from high-resolution aerial images and then computing landscape metrics in a geographic information system (GIS) environment.

This research and monitoring effort will attempt to answer the following key research questions:

- What is the level of overall disturbance attributed to gas exploration and development activities and how has this disturbance changed over time?
- What are the structural components (land cover classes) of this change and how much change can be attributed to each class?
- How has the disturbance associated with natural gas exploration and development affected the structure, pattern, and process of key ecosystems, especially forests, within the Marcellus Shale Play?
- How will the disturbance stressors affect ecosystem structure and function at a landscape and watershed scale?

## Landscape Metrics and a Landscape Perspective

An important and sometimes overlooked aspect of contemporary gas exploration activity is the geographic profile and spatial arrangement of these activities on the land surface. The function of ecosystems and the services they provide are due in large part to their spatial arrangement on the landscape. Energy exploration and development represents a specific form of land use and land cover change (LULCC) activity that substantially alters certain critical aspects of the spatial pattern, form, and function of landscape interactions.

Changes in land use and land cover affect the ability of ecosystems to provide essential ecological goods and services, which, in turn, affect the economic, public health, and social benefits that these ecosystems provide. One of the great scientific challenges for geographic science is to understand and calibrate the effects of LULCC and the complex interaction between human and biotic systems at a variety of natural, geographic, and political scales (Slonecker and others, 2010).

LULCC, such as the disturbance and the landscape effects of energy exploration, is currently occurring at a relatively rapid pace that is prompting immediate scientific focus and attention. Understanding the dynamics of land surface change requires an increased understanding of the complex nature of human-environmental systems and requires a suite of scientific tools that includes traditional geographic data and analysis methods, such as remote sensing and GIS, as well as innovative approaches to understanding the dynamics of complex natural systems (O’Neill and others, 1997; Turner, 2005; Wickham and others, 2007). One such approach that has gained much recent scientific attention is the landscape indicator, or landscape assessment, approach, which has been developed with the science of landscape ecology (O'Neill and others, 1997).

Landscape assessment utilizes spatially explicit imagery and GIS data on land cover, elevation, roads, hydrology, vegetation, and in situ sampling results to compute a suite of numerical indicators known as **landscape metrics** to assess ecosystem condition. Landscape analysis is focused on the relation between pattern and process and broad-scale ecological relationships such as habitat, conservation, and sustainability. Landscape analysis necessarily considers both biological and socioeconomic issues and relationships. This research explores these relationships and their potential effect on various ecosystems and biological endpoints.

The landscape assessment presented here is based largely on the framework outlined in O'Neill and others (1997). Many landscape metrics can be computed and utilized for some analytical purpose. However, it has been shown by several researchers (Riitters and others, 1995; Wickham and Riitters, 1995; Wickham and others, 1997) that many of these metrics are highly correlated, sensitive to misclassification and pixel size, and, to some extent, questionable in terms of additional information value. The key landscape concepts and metrics reported here are discussed below. The actual formulae used to compute these specific metrics can be found in software documentation for FRAGSTATS (McGarigal and others, 2002) and Analytical Tools Interface for Landscape Assessments (ATtILA) (Ebert and Wade, 2004). Computation details for percent interior forest and percent edge forest are documented by Riitters and others (2000).

The concept of landscape metrics, sometimes called landscape indices, is derived from the field of landscape ecology and is rooted in the realization that pattern and structure are important components of ecological process. Landscape metrics are spatial/mathematical indices that allow the objective description of different aspects of landscape structures and patterns (McGarigal and others, 2002). They characterize the landscape structure and various processes at both landscape and ecosystem levels. Metrics such as average patch size, fragmentation, and interior forest dimension capture spatial characteristics of habitat quality and potential change effects on critical animal and vegetation populations.

Two different geostatistical landscape analysis programs were used to measure the landscape metrics presented in this report. FRAGSTATS (University of Massachusetts, Amherst, Mass.) is a spatial pattern analysis program for quantifying numerous landscape metrics and their distribution and is available at *http://www.umass.edu/landeco/research/fragstats/fragstats.html* (McGarigal and others, 2002). ATtILA (U.S. Environmental Protection Agency (USEPA), Las Vegas, Nev.) is an Esri (Environmental Systems Research Institute, Redlands, Calif.) Arcview 3.x extension that computes a number of landscape, riparian, and watershed metrics and is available at *http://www.epa.gov/esd/land-sci/attila/* (Ebert and Wade, 2004). Metrics are presented here at the county level and mapped at the watershed level (12-digit Hydrologic Unit Codes).

## Disturbance

Disturbance is a key concept in a landscape analysis approach and in ecology in general. Gas development activities create a number of disturbances across a heterogeneous landscape. In landscape analysis, disturbances are discrete events in space and time that disrupt ecosystem structure and function and change resource availability and the physical environment (White and Pickett, 1985; Turner and others, 2001). When natural or anthropogenic disturbance occurs in natural systems, it generally alters abiotic and biotic conditions that favor the success of different species, such as opportunistic invasive species over predisturbance organisms. Natural gas exploration and development result in spatially explicit patterns of landscape disturbance involving the construction of well pads and impoundments, roads, pipelines, and disposal activities, which have structural impacts on the landscape (fig. 2).

Development of multiple sources of natural gas will result in increased traffic from construction, drilling operations (horizontal and vertical), hydraulic-fracturing, extraction, transportation, and maintenance activities. The mere presence of humans, construction machinery, infrastructure (for example, well pads and pipelines), roads, and vehicles alone may substantially impact flora and fauna. Increased traffic, especially rapid increases on roads that have historically received little activity, can have detrimental impacts to populations (Gibbs and Shriver, 2005). Forest loss as a result of disturbance, fragmentation, and edge effects has been shown to negatively affect water quality and runoff (Wickham and others, 2008), to alter biosphere-atmosphere dynamics that could contribute to climate change (Hayden, 1998; Bonan, 2008), and to affect the long-term survival of the forest itself (Gascon and others, 2007).

The initial step of landscape analysis is to determine the spatial distribution of disturbance to identify relative hotspots of activity. Disturbance in this report is presented as both graphic files and tables of summary statistics. This knowledge allows greater focus to be placed on specific locations. Figure 5 provides an example of the distribution of natural gas extraction in Bradford County, Pennsylvania, and it also shows how that disturbance is placed with respect to the local land cover.

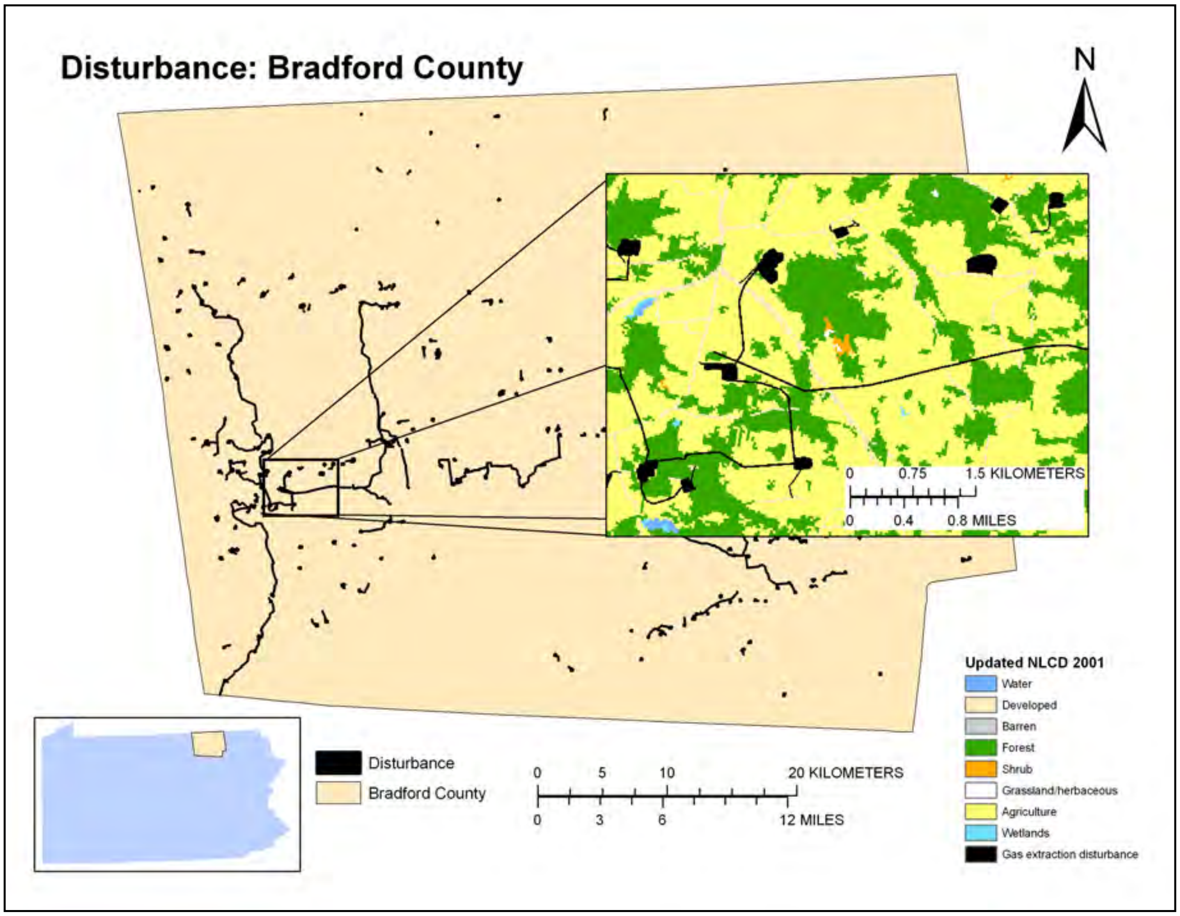

**Figure 5.** Example of a natural gas disturbance footprint from Bradford County, Pennsylvania, embedded within the National Land Cover Database (NLCD) 2001. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

## Forest Fragmentation

Forest fragmentation is the alteration of forest into smaller, less functional areas. Fragmentation of forest and habitat is a primary concern resulting from current gas development. Habitat fragmentation occurs when large areas of natural landscapes are intersected and subdivided by other, usually anthropogenic, land uses leaving smaller patches to serve as habitat for various species. As human activities increase, natural habitats, such as forests, are divided into smaller and smaller patches that have a decreased ability to support viable populations of individual species. Habitat loss and forest fragmentation can be important threats to biodiversity, although research on this topic has not been conclusive (With and Pavuk, 2011).

Although many human and natural activities result in habitat fragmentation, gas exploration and development activity can be extreme in their effect on the landscape. The development of numerous secondary roads and pipeline networks crisscross and subdivide habitat structure.

Landscape disturbance associated with shale-gas development infrastructure directly alters habitat through loss, fragmentation, and edge effects, which, in turn, alter the flora and fauna dependent on that habitat. The fragmentation of habitat is expected to amplify the problem of total habitat area reduction for wildlife species, as well as contribute toward habitat degradation. Fragmentation alters the landscape by creating a mosaic of spatially distinct habitats from originally contiguous habitat, resulting in smaller patch size, greater number of patches, and decreased interior to edge ratio (Lehmkuhl and Ruggiero, 1991; Dale and others, 2000). Fragmented habitats generally result in detrimental impacts to flora and fauna, caused by increased mortality of individuals moving between patches, lower recolonization rates, and reduced local population sizes (Fahrig and Merriam, 1994). The remaining patches may be too small, isolated, and possibly too influenced by edge effects to maintain viable populations of some species. The rate of landscape change can be more important than the amount or type of change because the temporal dimension of change can affect the probability of recolonization for endemic species, which are typically restricted by their dispersal range and the kinds of landscapes in which they can move (Fahrig and Merriam, 1994).

While general assumptions and hypotheses can be derived from existing scientific literature involving similar stressors, the specific impacts of habitat loss and fragmentation in the Marcellus Shale Play will depend on the needs and attributes of specific species and communities. A recent analysis of Marcellus well permit locations in Pennsylvania found that well pads and associated infrastructure (roads, water impoundments, and pipelines) required nearly 3.6 hectares (ha) per well pad, with an additional 8.5 ha of indirect edge effects (Johnson, 2010). This type of extensive and long-term habitat conversion has a greater impact on natural ecosystems than activities such as logging or agriculture, given the great dissimilarity between gas-well pad infrastructure and adjacent natural areas and the low probability that the disturbed land will revert back to a natural state in the near future (high persistence) (Marzluff and Ewing, 2001). Figure 6 shows an example of the concept of the landscape metric of forest fragmentation.

## Interior Forest

Interior forest is a special form of habitat that is preferred by many plant and animal species and is defined as the area of forest at least 100 m from the forest edge (Harper and others, 2005). Interior forest is an important landscape characteristic because the environmental conditions, such as light, wind, humidity, and exposure to predators, within the interior forest are different from areas closer to the forest edge. Interior forest habitat is related to the size and distribution of forest patches and is closely tied to the concept of forest or habitat **fragmentation**. The amount of interior forest can be dramatically affected by linear land use patterns, such as roads and pipelines, which tend to fragment land patches into several smaller patches and destroy available habitat for certain species. Figure 6 shows the general concept of increased fragmentation and reduced interior forest.

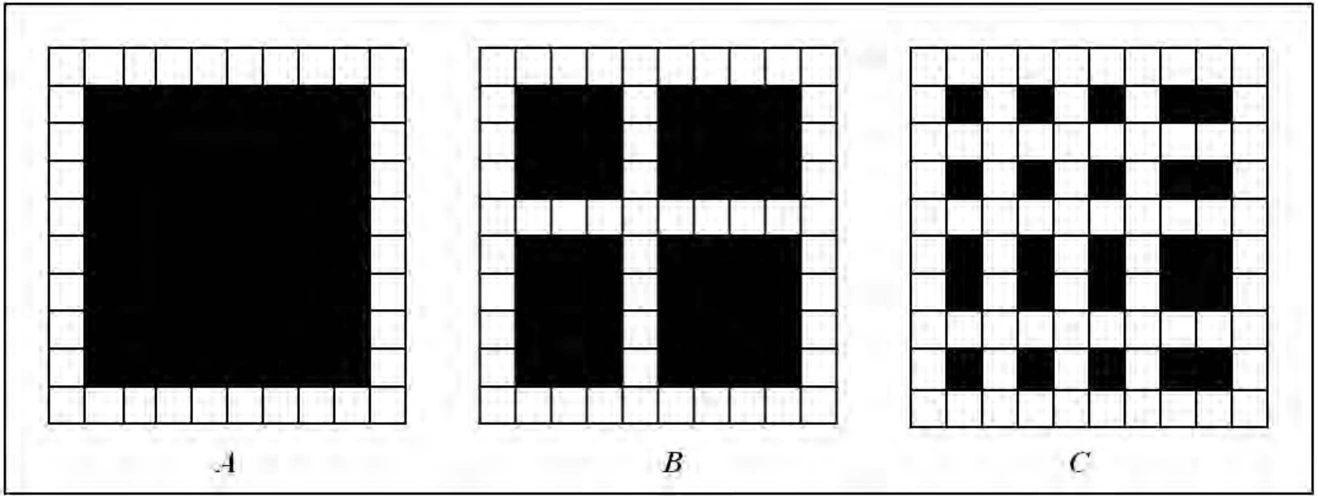

**Figure 6.** Conceptual illustration of interior forest and how this critical habitat is affected by linear disturbance. (*A*) High interior area, (*B*) Moderate interior area, and (*C*) Low interior area (Riitters and others, 1996).

## Forest Edge

Forest edge is simply a linear measure of the amount of edge between forest and other land uses in a given area, and especially between natural and human-dominated landscapes. The influence of the two bordering communities on each other is known as the edge effect. When edges are expanded into natural ecosystems, and the area outside the boundary is a disturbed or unnatural system, the natural ecosystem can be affected for some distance in from the edge (Skole and Tucker, 1993). Edge effects are variable in space and time. The intensity of edge effects diminishes as one moves deeper inside a forest, but edge phenomena can vary greatly within the same habitat fragment or landscape (Laurance and others, 2007). Factors that might promote edge-effect variability include the age of habitat edges, edge aspect, and the combined effects of multiple nearby edges, fragment size, seasonality, and extreme weather events.

Spatial variability of edge effects may result from local factors, such as the proximity and number of nearby forest edges. Plots with two or more neighboring edges, such as smaller fragment plots, have greater tree mortality and biomass loss than larger plots with less edges. Edge age also influences edge effects. Over time, forest edge is partially sealed by proliferating vines and second growth underbrush, which will influence the ability of smaller tree seedlings to survive in this environment. Likewise, the matrix of adjoining vegetation plots will have a strong influence on edge effects. Forest edges adjoined by young regrowth forest provide a physical buffer from wind and light. Extreme weather events also affect the temporal variability in edge effects. Abrupt, artificial boundaries of forest fragments are vulnerable to windstorms, snow and ice, and convectional thunderstorms that can weaken and destroy exposed forest edges. Periodic droughts can also have a more pronounced effect on forest edges that are exposed to drier wind conditions and higher rates of evaporation than found in interior forests.

## Contagion

Contagion is an indicator that measures the degree of “clumpiness” among the classes of land cover features and is related to patch size and distribution. Contagion expresses the degree to which adjacent pixel pairs can be found in the landscape. Figure 7 shows the general concept of contagion and gives examples of low, medium, and high contagion. Contagion is valuable because it relates an important measure of how landscapes are fragmented by patches. Landscapes of large, less-fragmented patches have a high contagion value, and landscapes of numerous small patches have a low contagion value (McGarigal and others, 2002).

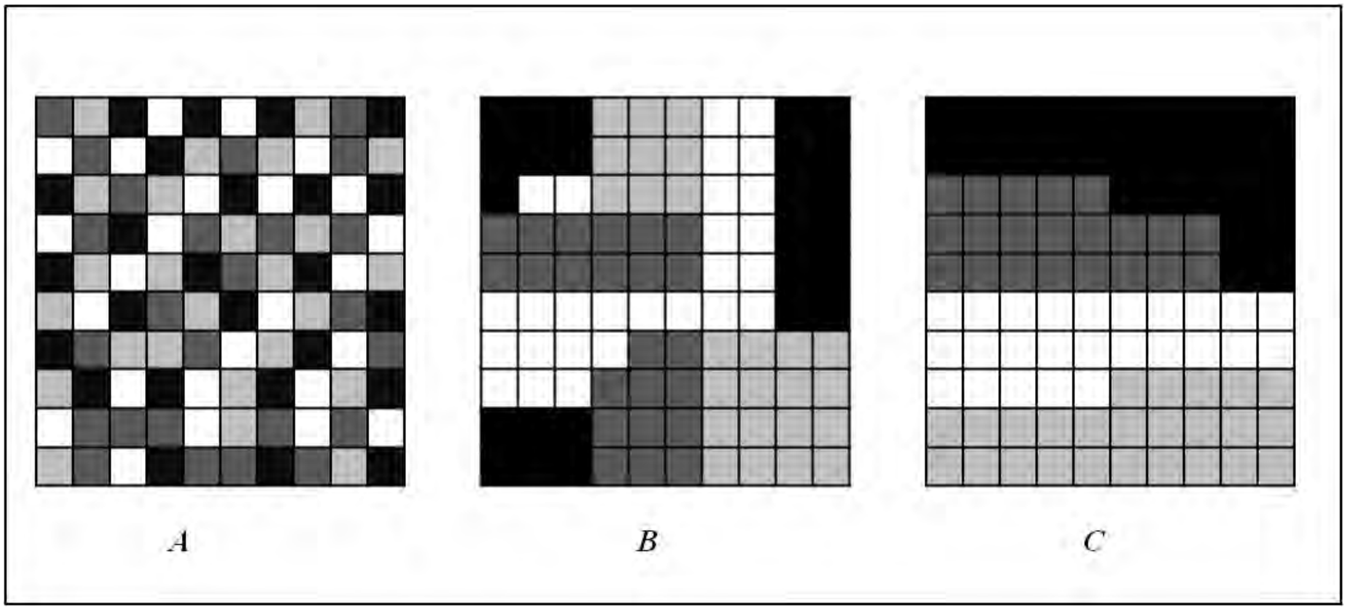

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or “clumped” to one another. *(A)* Low contagion, *(B)* Moderate contagion, and *(C)* High contagion (after Riitters and others 1996).

## Fractal Dimension

Fractal dimension describes the complexity of patches or edges within a landscape and is generally related to the level of anthropogenic influence in a landscape. Fractal dimension generally measures the perimeter-to-area proportional relationship of a patch. Human land uses tend to have simple, circular, or rectangular shapes of low complexity and, therefore, low fractal dimensions. Natural land covers have irregular edges, complex arrangements and, therefore, higher fractal dimensions. The fractal dimension index ranges between 1 and 2, with 1 indicating high human influences in the landscape and 2 with natural patterns and low human influence (McGarigal and others, 2002).

## Dominance

Dominance is a measure of the relative abundance of different patch types, typically emphasizing either relative evenness or equity in the distribution. Dominance is high when one land cover type occupies a relatively large area of a given landscape and is low when land cover types are evenly distributed. Dominance is the complement to evenness, which is sometimes used as an alternative measure of the relative area of one land cover type over others in the landscape.

Although there are many metrics associated with dominance, here we report on a simple landscape metric—the Simpson's Evenness Index, which is a measure of the proportion of the landscape occupied by a patch type divided by the total number of patch types in the landscape (McGarigal and others, 2002).

## Methodology: Mapping and Measuring Disturbance Effects

High-resolution aerial imagery for each of four timeframes—2004, 2005/2006, 2008, and 2010—were brought into a GIS database, along with additional geospatial data on Marcellus and non-Marcellus well permits and locations, administrative boundaries, ecoregions, and geospatial information on the footprint of the Marcellus Shale Play in Pennsylvania. The imagery was examined for distinct signs of disturbance related to oil and gas drilling and development. The observable features were manually digitized as line and polygon features in a GIS format. The polygons and line features were processed and aggregated into a raster mask used to update existing land cover data. Summary statistics for each county were developed and reported. Detailed landscape metrics were calculated and mapped over watersheds within and intersecting the boundary of each county.

### Data

#### Sources

High-resolution aerial imagery from the National Agriculture Imagery Program (NAIP) was downloaded for each timeframe. NAIP imagery is flown to analyze the status of agricultural lands approximately every 2 to 3 years (U.S. Department of Agriculture, Farm Service Agency, 2011). The NAIP imagery consists of readily available, high-resolution data that are suitable for detailed analysis of the landscape. NAIP imagery is available from the U.S. Department of Agriculture Geospatial Data Gateway Web site (U.S. Department of Agriculture, Natural Resources Conservation Service, 2011). Table 1 identifies the source imagery dates for each county and year.

**Table 1.** Acquisition dates of National Agriculture Imagery Program (NAIP) source data.

| Year | Source imagery dates (chronological from left to right) | | | | | |
|---|---|---|---|---|---|---|
| | | | Allegheny County | | | |
| 2004 | 2004-06-20 | 2004-07-03 | 2004-08-02 | 2004-09-01 | 2004-09-03 | 2004-10-07 |
| 2005 | 2005-06-23 | 2005-08-24 | 2005-09-07 | 2005-09-10 | 2005-09-11 | |
| 2006 | 2006-10-07 | 2006-10-08 | | | | |
| 2008 | 2008-06-07 | 2008-07-02 | 2008-07-15 | 2008-07-18 | 2008-07-29 | 2008-09-03 |
| 2010 | 2010-06-08 | 2010-06-18 | 2010-08-31 | 2010-09-02 | | |
| | | | Susquehanna County | | | |
| 2004 | 2004-06-12 | 2004-06-21 | 2004-08-23 | 2004-09-20 | | |
| 2005 | 2005-06-23 | 2005-06-24 | | | | |
| 2006 | | | | | | |
| 2008 | 2008-06-13 | 2008-09-02 | 2008-09-04 | 2008-10-10 | | |
| 2010 | 2010-07-11 | 2010-08-07 | 2010-09-01 | | | |

Drilling permits for Marcellus Shale and non-Marcellus Shale natural gas were obtained from the Pennsylvania Department of Environmental Protection Permit and Rig Activity Reports for 2004–2010 (Pennsylvania Department of Environmental Protection, Office of Oil and Gas Management, 2011).

The U.S. Geological Survey (USGS) Watershed Boundary Dataset 12-digit Hydrologic Unit Code (HUC12) for Pennsylvania was downloaded from the USGS National Hydrography Dataset Web site (U.S. Geological Survey, 2011b).

The Marcellus Shale Play assessment unit boundaries were downloaded from the USGS Energy Resources Program Data Services Web site (U.S. Geological Survey, 2012).

The 2001 National Land Cover Database (NLCD) was acquired for use as the baseline land cover map. The NLCD is a 16-class land cover classification scheme applied consistently across the United States at a 30-m spatial resolution (Homer and others, 2007). The NLCD may be acquired using the Multi-Resolution Land Characteristics Consortium Web site (U.S. Geological Survey, 2011c). The NLCD 2001 was resampled to 10-m pixel size.

### Collection

These data were brought into a GIS database for spatial analysis. Using the 2004 imagery as a baseline, the imagery was examined for distinct signs of disturbance related to oil and gas drilling and development. These mapped features include the following:

- Sites—Cleared areas related to existing permits or displaying the characteristics of a shale or coalbed gas extraction site.
- Roads—Vehicular transportation corridors constructed specifically for shale or coalbed gas development.
- Pipelines—New gas pipelines constructed in conjunction with one or more well pads.
- Impoundments—Manmade depressions designed to hold liquid and in support of oil and gas drilling operations.
- Other—Support areas or activities such as processing plants, storage tanks, and staging areas.

The collection of gas extraction infrastructure was a manual process of visually examining high-resolution imagery for each county over four dates to identify and digitize (collect) changes in the land cover resulting from the development of gas extraction infrastructure. Specifically, we examined NAIP 1-m data composited for the years 2004, 2005/2006, 2008, and 2010, identifying landscape changes that occurred after 2004.

Changes that correlated with natural gas extraction permits, appeared to be natural gas extraction related, or were in proximity to other gas extraction infrastructure were selected and digitized to the maximum extent of landscape disturbance. The focus of the data collection was on features attributable to the construction, use, and maintenance of gas extraction drill sites, processing plants, and compressor stations, as well as the center lines for new roads accessing such sites, plants, and stations, and the center lines for new pipelines used to transport the extracted gas. Figure 8 shows examples of digitized natural gas extraction features. These data were collected within shapefiles per county, using ArcGIS 10.0. One shapefile was generated for sites (polygons), one was generated for roads (lines), and one was generated for pipelines (lines). Roads and pipelines were generally buffered to 8 and 12 m, respectively, for overall area assessments. The buffered distance was selected as the average from measurement of roads and pipelines in the counties. All sites were initially classified as gas extraction related or points of interest. Points of interest were unlikely to be related to drilling but were of potential future interest and excluded from further processing. All data collected were reviewed by another team member for concurrence and consistency.

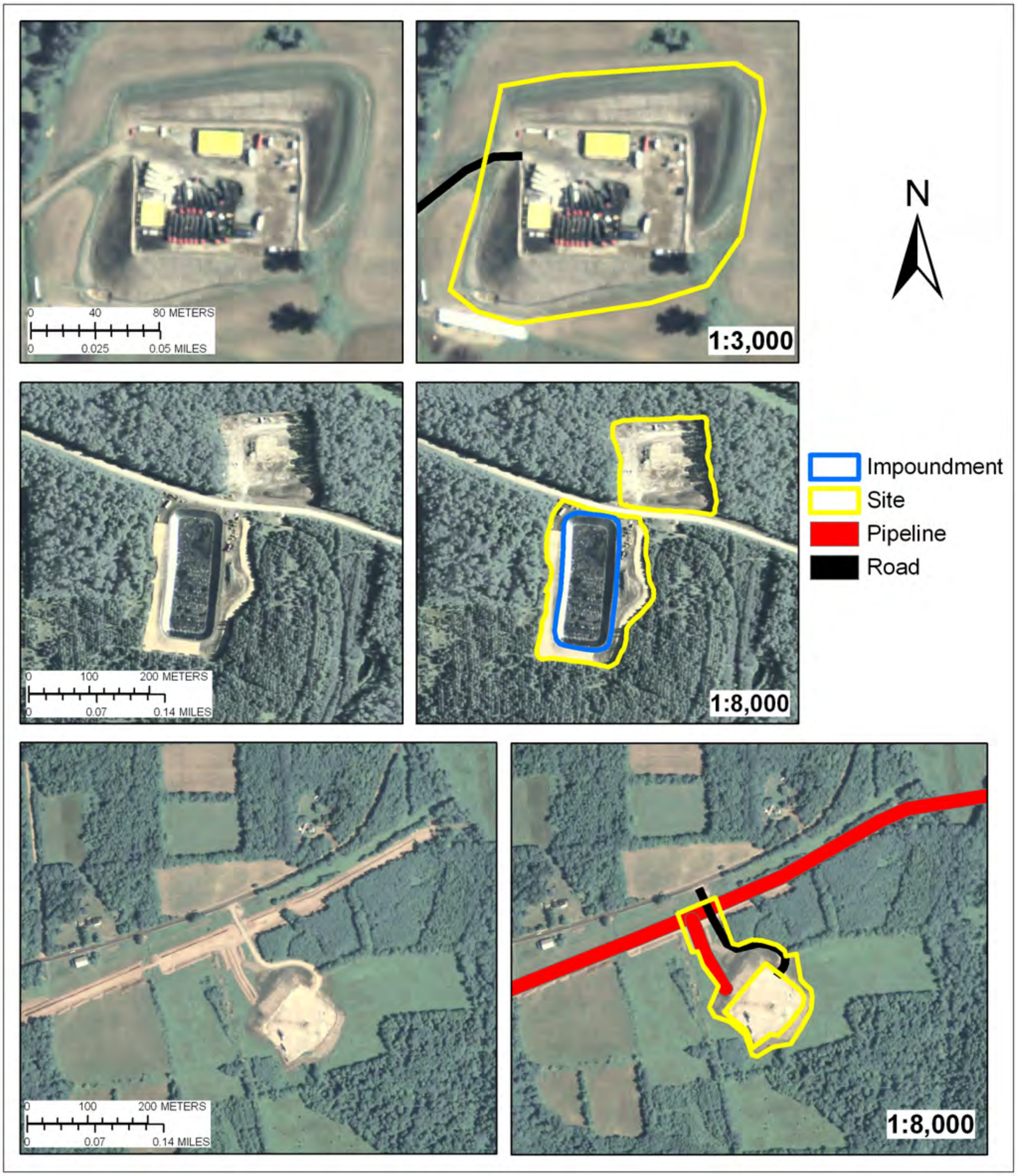

**Figure 8.** Examples of spatially explicit features of disturbance that were extracted from aerial photographs into a geographic information system (GIS) format.

## Land Cover Update

Using the collected and reviewed data, the polygons and line features were processed and aggregated into a raster format used as a mask to update existing land cover data from NLCD 2001. Figure 9 shows the processing flow to accomplish this task consistently across both counties.

Each feature within the shapefiles was then processed to determine its permit status and area. Each county's shapefiles were then merged and internal boundaries dissolved, the result of which was a disturbance footprint for that county. The disturbance footprint was then rasterized and used to conditionally select the pixels in the 2001 NLCD to reclassify as a new class: gas extraction disturbance. To consistently perform this processing, a set of models was developed using the ArcGIS ModelBuilder.

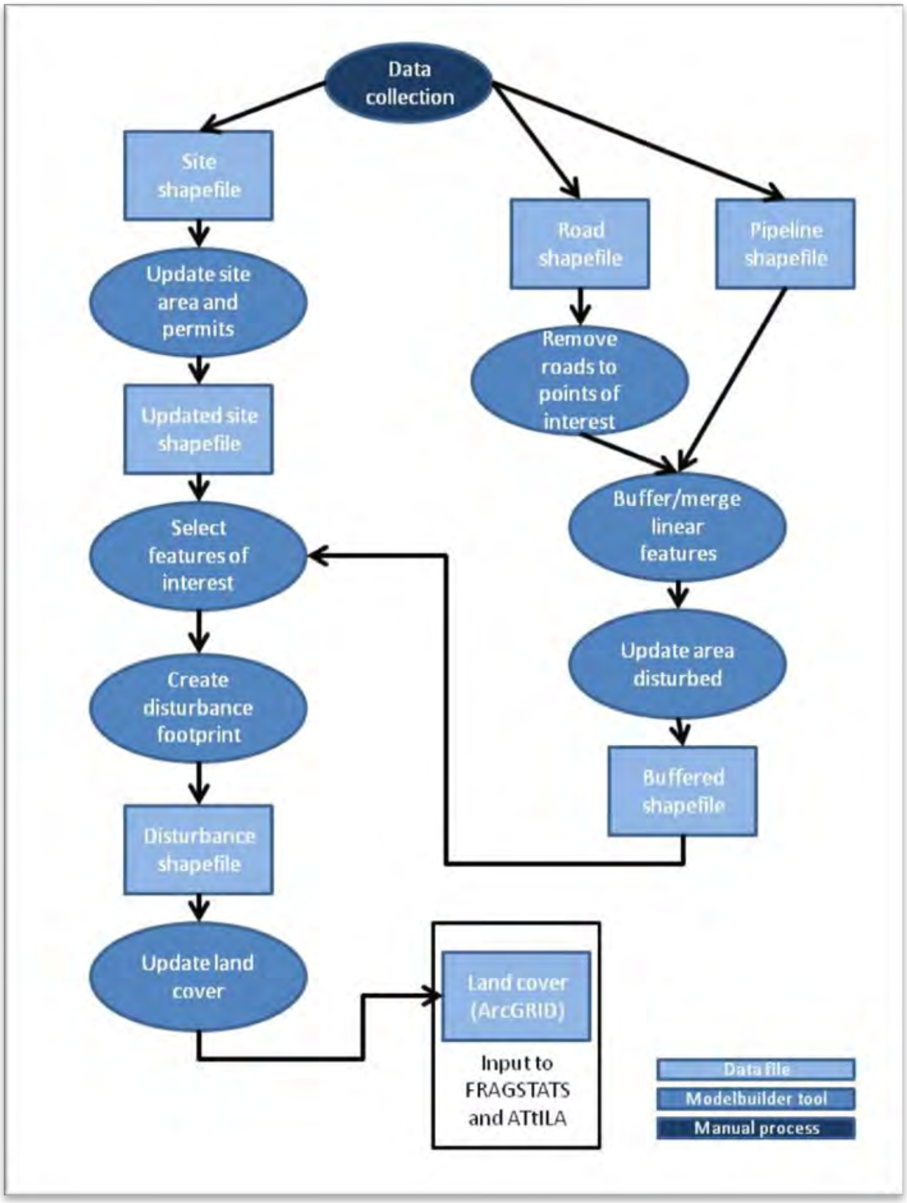

**Figure 9.** Workflow diagram for creating an updated land cover map. The workflow is implemented using ArcGIS ModelBuilder scripts to process the digitized data and embed in the resampled NLCD 2001.

### Calculation of Landscape Metrics

Landscape-wide and land cover class fragmentation statistics for each county were developed and reported using FRAGSTATS, while land cover class-detailed statistics, forest fragmentation statistics, including patch metrics and forest condition (interior, edge, and so forth) metrics, were calculated over smaller watersheds (HUC12) intersecting with the county using ATtILA. The collected statistics were then summarized, charted, and mapped for further analysis.

In addition to the summary of features noted above, a series of landscape metrics was calculated for each county based on the change related to gas development activities between 2004 and 2010. To do this, the metrics were calculated from the 2001 NLCD dataset (Homer and others, 2007). Following that calculation, the 2004–2010 cumulative spatial pattern of disturbance was digitally embedded into the 2001 NLCD dataset and the metrics were recalculated for each county.

## Results: Summary Statistics and Graphics

This section presents a summary of landscape alterations from natural gas resource development, along with the ensuing change in land cover and landscape metrics for each county using metrics suggested by O'Neill and others (1997). These metrics are then calculated and presented based on the sources of that disturbance: Marcellus sites and roads; non-Marcellus sites and roads; and other infrastructure, which includes nonpermitted sites, processing facilities and their associated roads; and pipelines and their associated roads. Nonpermitted sites are defined as disturbed areas that appear to be Marcellus or non-Marcellus gas extraction sites that do not have a permit within 250 m of the disturbance. These data are presented in tabular form with some graphic presentations provided where appropriate. Examples of the spatial distribution of selected landscape metrics are shown at the watershed level for each county. GIS data of all disturbance features are available upon request.

### Disturbed Area

Documenting the spatially explicit patterns of disturbance was one of the primary goals of this research, and this section describes the extent of disturbed land cover for Allegheny and Susquehanna Counties in Pennsylvania. The spatial distribution of disturbance influences the impacts of that disturbance. Figure 10 shows the distribution of disturbance within Allegheny and Susquehanna Counties. In Allegheny County, disturbance is clustered along the eastern edge of the county, with the greatest concentration in the northeast. Most of this disturbance is non-Marcellus related. In Susquehanna County, disturbance is clustered in the southwest quadrant and is related to Marcellus Shale natural gas extraction. The detailed insets show the disturbance footprints in the context of the surrounding land cover.

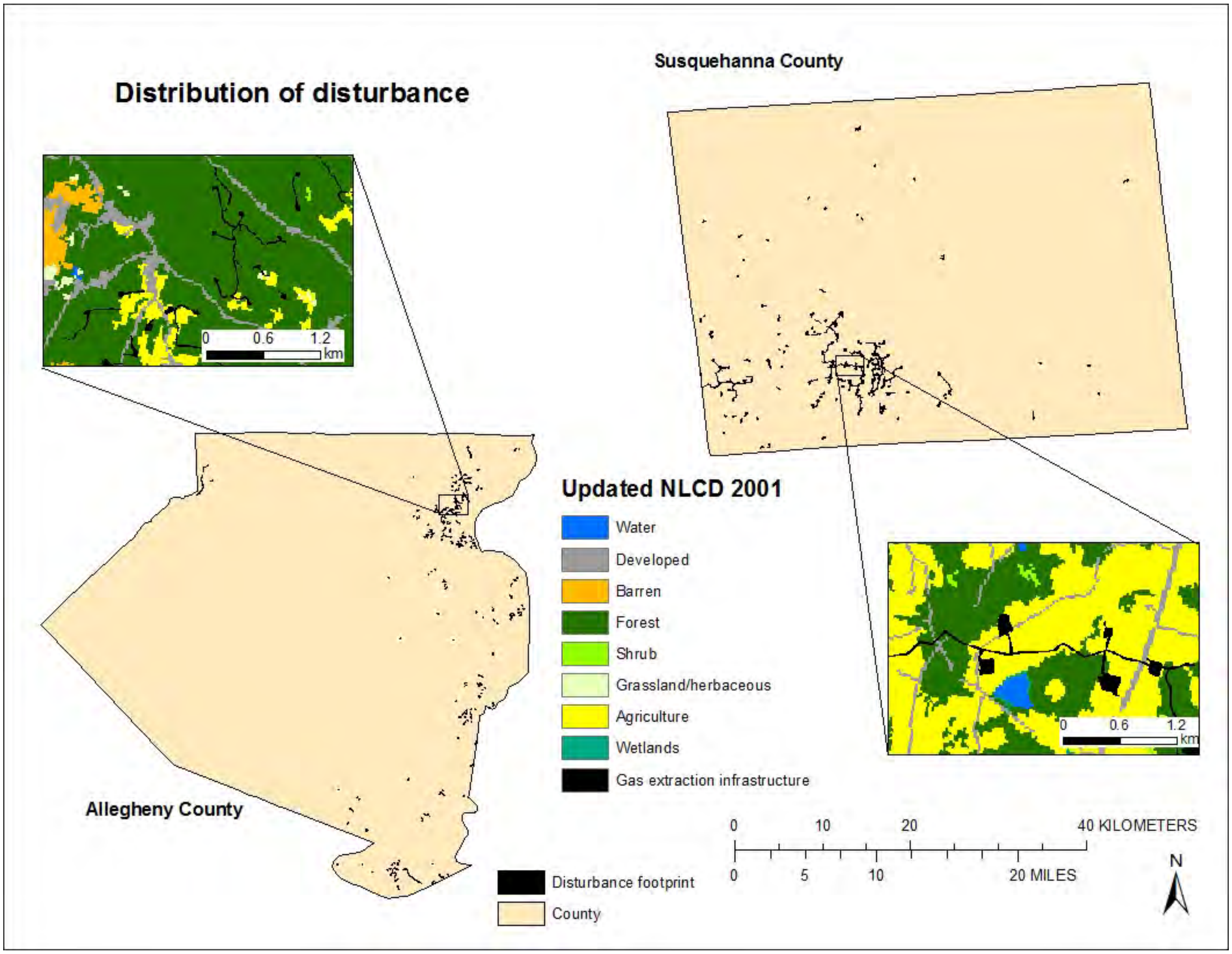

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Allegheny and Susquehanna Counties, Pennsylvania. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

Table 2 lists the disturbance area attributable to all sites and impoundments and their associated roads and pipelines. The disturbance area is presented first as a total disturbance for all gas extraction infrastructure, including all sites, roads, and pipelines. Total disturbance is then divided into sections; the first includes disturbance for all sites and their associated roads, and the second includes disturbance for pipelines and impoundments. The disturbance area for all sites and roads is further divided into disturbance for Marcellus Shale permitted sites and roads, non-Marcellus Shale permitted sites and roads, sites lacking an identifiable permit (for example, processing facilities or incomplete permit data), and sites with permits for both Marcellus and non-Marcellus drilling. Additionally, the disturbance area associated with impoundments is presented for those impoundments greater than 0.4 ha and for those less than 0.4 ha. Because land disturbance or access roads may be associated with multiple infrastructural components (for example, pipelines may cross areas also disturbed for drill sites), the values for disturbed areas and road miles within break-out categories such as “MS sites and roads” do not sum up to the higher level category, in this instance, “All sites and roads.” The results indicate the following:

- While Allegheny and Susquehanna Counties are roughly equal in size (192,000 and 216,000 ha, respectively), Allegheny County has one-third the number of Marcellus sites with 39 sites compared to 151 sites in Susquehanna County. In contrast, Allegheny has 40 times the number of non-Marcellus sites as in Susquehanna (468 and 11 sites, respectively).
- The mean number of hectares of disturbance per site is smaller (0.8 ha) in Allegheny County than in Susquehanna (2.4 ha) because of the greater number of smaller non-Marcellus sites.
- The mean number of disturbed hectares for Marcellus sites is greater for Susquehanna County (3.1 ha) than for Allegheny (2.2 ha), while the mean number of disturbed hectares per non-Marcellus site is approximately four times larger in Susquehanna (3.4 ha) than in Allegheny (0.7 ha). A visual examination of the Susquehanna non-Marcellus sites reveals several large sites, which include multiple wells or impoundments that may be related to hydraulic fracturing for coalbed methane production.
- Allegheny County has approximately five times the number of "other" sites (processing and transportation facilities and nonpermitted sites) than Susquehanna County (132 and 24 sites, respectively). The Allegheny sites appear to be mainly nonpermitted. The Allegheny sites also have a smaller mean size than the Susquehanna sites (0.9 ha versus 2.2 ha).
- Allegheny County has approximately six times the number of large (>0.4 ha) impoundments as in Susquehanna County (63 and 10 impoundments, respectively) and approximately five times the number of small (<0.4 ha) impoundments (284 and 51, respectively). The mean size of large impoundments is similar for both counties, as is the mean size of small impoundments.

Land cover change is the initial impact of disturbance and can have long-term effects on ecological integrity and functions. Table 3 lists the percent land cover by county for 2001 and percent land cover and change for the updated 2010 landscape. The land cover change for the updated landscape is further divided into the values attributable to Marcellus sites, non-Marcellus sites, other infrastructure including nonpermitted sites, and pipelines, each with their associated roads. Given that the natural land cover of Pennsylvania is forest (Kuchler, 1964), the 2001 land cover provides a measure of the impacts prior to most natural gas resource development; the changes between 2004 and 2010 have only increased these impacts. Of particular interest are the forest cover and its relation to the critical value 59.28 percent from percolation theory (Gardner and others, 1987; O'Neill and others, 1997). Below this value, the landscape structure rapidly breaks down into isolated patches, thereby changing forest resilience and habitat corridors. The results indicate the following:

- In both Allegheny and Susquehanna Counties, the primary land covers are forest (41 percent and 64 percent, respectively), agriculture (5 percent and 28 percent, respectively), and developed (51 percent and 4 percent, respectively). The high level of development in Allegheny County may be attributed to the city of Pittsburgh and its surrounding suburbs.
- Allegheny County had less than the critical amount of forest in 2001, and that forest has been further impacted by natural gas resource development. Percent forest declined by 0.07 percent (134.7 ha).
- Susquehanna County had greater than the critical amount of forest in 2001. That forest has declined by 0.09 percent (194.3 ha) from natural gas resource development.
- Susquehanna County agriculture declined by 0.17 percent (367.1 ha) from natural gas resource development.

**Table 2.** Cumulative amount of landscape disturbance for natural gas extraction development and infrastructure based on disturbance type from 2004 to 2010 by county.

[Note: Categories are not mutually exclusive. MS, Marcellus Shale site; non-MS, non-Marcellus Shale site; >, greater than, <, less than]

| Land cover update | Count | Site only hectares | Footprint disturbed hectares | Road kilometers | Pipeline kilometers | Hectares per site | Disturbed hectares per site | Road kilometers per site |
|---|---|---|---|---|---|---|---|---|
| Allegheny County (192,342 hectares) | | | | | | | | |
| All infrastructure | 647 | 364.8 | 531.5 | 226.7 | 13.2 | 0.6 | 0.8 | 0.3 |
| All sites and roads | 633 | 332.38 | | | | | | |
| MS sites and roads | 39 | 76.7 | 86.6 | 10.9 | | 2 | 2.2 | 0.3 |
| Non-MS sites and roads | 468 | 207.5 | 349.9 | 117.7 | | 0.4 | 0.7 | 0.3 |
| Other infrastructure/ nonpermitted sites and roads | 132 | 63.3 | 120 | 69.5 | | 0.5 | 0.9 | 0.5 |
| Dual sites | 7 | 15.2 | | | | 2.2 | | |
| Pipelines | 14 | 32.34 | 27.3 | 2.9 | 13.2 | 2.3 | | |
| Impoundments (>0.4 hectares) | 63 | 56.3 | | | | 0.9 | | |
| Impoundments (<0.4 hectares) | 284 | 31.3 | | | | 0.1 | | |
| Susquehanna County (216,043 hectares) | | | | | | | | |
| All infrastructure | 294 | 680.2 | 705.8 | 55.3 | 86.9 | 2.3 | 2.4 | 0.2 |
| All sites and roads | 178 | 446.5 | | | | | | |
| MS sites and roads | 151 | 419 | 468.4 | 50.4 | | 2.8 | 3.1 | 0.3 |
| Non-MS sites and roads | 11 | 29.8 | 37.3 | 6.1 | | 2.7 | 3.4 | 0.5 |
| Other infrastructure/ nonpermitted sites and roads | 24 | 43.3 | 53.5 | 7.9 | | 1.8 | 2.2 | 0.3 |
| Dual sites | 11 | 26.9 | | | | 2.4 | | |
| Pipelines | 116 | 213.6 | 235.1 | 21.2 | 86.9 | 1.9 | | |
| Impoundments (>0.4 hectares) | 10 | 10.7 | | | | 1.1 | | |
| Impoundments (<0.4 hectares) | 51 | 4 | | | | 0.3 | | |

**Table 3.** Percent land cover (2001) and land cover change (2010) calculated for each county.

[MS, Marcellus Shale site; non-MS, non-Marcellus Shale site]

| Land cover | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Allegheny County | | | | | | | | | | | |
| Forest | 41.33 | 41.26 | -0.07 | 41.33 | 0 | 41.28 | -0.05 | 41.31 | -0.02 | 41.33 | 0 |
| Agriculture | 5.12 | 5.11 | -0.01 | 5.12 | 0 | 5.12 | -0.01 | 5.12 | 0 | 5.12 | 0 |
| Developed | 50.87 | 50.86 | -0.01 | 50.87 | 0 | 50.86 | -0.01 | 50.87 | 0 | 50.87 | 0 |
| Grassland-herbaceous | 0.72 | 0.72 | 0 | 0.72 | 0 | 0.72 | 0 | 0.72 | 0 | 0.72 | 0 |
| Water | 1.78 | 1.78 | 0 | 1.78 | 0 | 1.78 | 0 | 1.78 | 0 | 1.78 | 0 |
| Barren | 0.14 | 0.14 | 0 | 0.14 | 0 | 0.14 | 0 | 0.14 | 0 | 0.14 | 0 |
| Wetlands | 0.03 | 0.03 | 0 | 0.03 | 0 | 0.03 | 0 | 0.03 | 0 | 0.03 | 0 |
| Scrub-shrub | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas extraction disturbance | | 0.09 | 0.09 | 0 | 0 | 0.06 | 0.06 | 0.03 | 0.03 | 0.01 | 0.01 |
| Susquehanna County | | | | | | | | | | | |
| Forest | 64.24 | 64.15 | -0.09 | 64.19 | -0.05 | 64.24 | 0 | 64.24 | -0.01 | 64.2 | -0.05 |
| Agriculture | 28.18 | 28.01 | -0.17 | 28.05 | -0.12 | 28.17 | -0.01 | 28.17 | -0.01 | 28.13 | -0.05 |
| Developed | 4.44 | 4.43 | -0.01 | 4.43 | -0.01 | 4.44 | 0 | 4.44 | 0 | 4.44 | 0 |
| Grassland-herbaceous | 0.1 | 0.1 | 0 | 0.1 | 0 | 0.1 | 0 | 0.1 | 0 | 0.1 | 0 |
| Water | 1.16 | 1.16 | 0 | 1.16 | 0 | 1.16 | 0 | 1.16 | 0 | 1.16 | 0 |
| Barren | 0.09 | 0.09 | 0 | 0.09 | 0 | 0.09 | 0 | 0.09 | 0 | 0.09 | 0 |
| Wetlands | 0.69 | 0.69 | 0 | 0.69 | 0 | 0.69 | 0 | 0.69 | 0 | 0.69 | 0 |
| Scrub-shrub | 1.1 | 1.1 | 0 | 1.1 | 0 | 1.1 | 0 | 1.1 | 0 | 1.1 | 0 |
| Gas extraction disturbance | | 0.28 | 0.28 | 0.18 | 0.18 | 0.02 | 0.02 | 0.02 | 0.02 | 0.1 | 0.1 |

## Land Cover Metrics of Interest

There are numerous landscape metrics, many of which are redundant. Table 4 lists the total area, number of patches, total edge, mean fractal index, contagion, and evenness metrics for the 2001 county landscape and the metrics and change for the updated 2010 landscape. The metrics and change for the updated landscape are further divided into the values attributable to Marcellus sites, non-Marcellus sites, other infrastructure including nonpermitted sites, and pipelines, each with their associated roads. These metrics were chosen for their overall indication of human impacts on the landscape and environmental quality (O'Neill and others, 1997). Increase in edge, especially between unlike land covers, indicates declining resilience of the natural land cover and movement of species, while the decrease in the mean fractal index ($1 \leq x \leq 2$) indicates an increase in human use. Evenness ($0 \leq x \leq 1$, where 0 indicates one land cover class and 1 indicates even distribution across land cover classes), indicates the relative heterogeneity of the landscape and is the inverse of the dominance measure (McGarigal and others, 2002) recommended by O'Neill and others (1997). Contagion ($0 < x \leq 100$, disaggregated to aggregated) is an indicator that measures the degree of "clumpiness" among the classes of land cover features. The results indicate the following changes occurred based on 2004-2010 natural gas development:

- Total edge increased by 177.8 kilometers and 283.6 kilometers for Allegheny and Susquehanna Counties, respectively, with the largest amount attributable to non-Marcellus development in Allegheny and to Marcellus site and pipeline development in Susquehanna.
- Mean fractal index is very low for both counties, indicating a high level of human influence in these counties.
- Contagion shows a moderate level of clumped land cover for both counties. The influence of infrastructure type (all, Marcellus, non-Marcellus, other, and pipelines) was similar for Allegheny but more variable for Susquehanna.
- Evenness also shows a moderate level of heterogeneity for both counties with no one land cover dominating.
- Evenness has similar values for each infrastructure type. Given that the expected land cover is all forest and an evenness value approaching zero, this value indicates a substantially disturbed landscape.

**Table 4.** Landscape metrics by county for 2001 (original land cover) and as updated for natural gas development disturbance (2004–2010).

[Note: Categories are not mutually exclusive. MS, Marcellus Shale site; non-MS, non-Marcellus Shale site]

| Metric | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infra-structure | Change | Updated with pipelines and roads | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Allegheny County | | | | | | | | | | | |
| Total area (hectares) | 192,337.5 | 192,337.5 | 0 | 192,337.5 | 0 | 192,337.5 | 0 | 192,337.5 | 0 | 192,337.5 | 0 |
| Number of patches | 7838 | 8278 | 440 | 7843 | 5 | 8129 | 291 | 7961 | 123 | 7887 | 49 |
| Total edge (kilometers) | 15,529.7 | 15,707.5 | 177.8 | 15,534 | 4.3 | 15,648.5 | 118.9 | 15,595 | 65.3 | 15,543.5 | 13.9 |
| Mean fractal index | 1.1195 | 1.1196 | 0.0001 | 1.1195 | 0 | 1.1196 | 0.0001 | 1.1197 | 0.0002 | 1.1195 | 0 |
| Contagion | 71.7896 | 73.0912 | 1.3016 | 73.2896 | 1.5 | 73.1569 | 1.3673 | 73.2224 | 1.4328 | 73.2775 | 1.4879 |
| Evenness | 0.5674 | 0.5681 | 0.0007 | 0.5674 | 0 | 0.5679 | 0.0005 | 0.5676 | 0.0002 | 0.5675 | 0.0001 |
| Susquehanna County | | | | | | | | | | | |
| Total area (hectares) | 216,036.2 | 216,036.2 | 0 | 216,036.2 | 0 | 216,036.2 | 0 | 216,036.2 | 0 | 216,036.2 | 0 |
| Total edge (kilometers) | 18,030.1 | 18,313.7 | 283.6 | 18,161.4 | 131.3 | 18,044.2 | 14.1 | 18,049.6 | 19.5 | 18,232.5 | 202.4 |
| Mean fractal index | 1.1279 | 1.1262 | -0.0017 | 1.1269 | -0.001 | 1.1277 | -0.0002 | 1.1278 | -0.0001 | 1.1272 | -0.0007 |
| Contagion | 72.814 | 73.8077 | 0.9937 | 73.9671 | 1.1531 | 74.2343 | 1.4203 | 74.2253 | 1.4113 | 74.0474 | 1.2334 |
| Evenness | 0.5056 | 0.5078 | 0.0022 | 0.5069 | 0.0013 | 0.5057 | 0.0001 | 0.5058 | 0.0002 | 0.5065 | 0.0009 |

## Forest Fragmentation

Disturbance in the landscape will affect forests by fragmentation, which is the process of dividing large land cover (for example, forest) into smaller segments called patches. A patch is defined as adjacent (forest) pixels, including diagonals. A landscape with many small patches is representative of a highly fragmented landscape. Fragmented forests provide habitat for edge species but are poor for interior species and are less likely to provide migration corridors.

Fragmentation may be evaluated by change in the number of patches and by change in the mean and (or) median patch size. Table 5 compares the changing forest patch metrics for the 2001 land cover, the updated 2010 land cover, and subsets of the updated 2010 land cover based on Marcellus infrastructure, non-Marcellus infrastructure, other infrastructure, and pipelines. The results indicate the following changes occurred based on 2004–2010 natural gas development:

- Forests became more fragmented due to natural gas resource development. Both Allegheny and Susquehanna Counties contained more, but smaller, forest patches in 2010 than in 2001.
- Allegheny County forest patches increased by 114; most (about 79 patches) are attributable to non-Marcellus development. These patches initially averaged about 25 ha, but that average was reduced by almost 1 ha in 2010.
- Susquehanna County forest patches increased by almost 156; most (about 121 patches) are attributable to pipeline construction. These patches initially averaged about 67.1 ha and were reduced by 4.8 ha to a mean of about 62.3 ha. Pipeline construction had the greatest effect on these values.
- Both Allegheny and Susquehanna Counties have large differences between the forest patch mean area and median area values: 25.0 ha mean to 1.8 ha median and 67.1 ha mean to 0.7 ha median, respectively. These large differences indicate a skewed population of forest patch sizes including many small forest patches and few large forest patches.

**Table 5.** Forest fragmentation metrics by county for 2001 (original land cover) and as updated for natural gas development disturbance (2004–2010).

[Note: Categories are not mutually exclusive. MS, Marcellus Shale site; non-MS, non-Marcellus Shale site]

| Distribution statistics | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Allegheny County | | | | | | | | | | | |
| Number of patches | 3,177 | 3,291 | 114 | 3,177 | 0 | 3,256 | 79 | 3,205 | 28 | 3,190 | 13 |
| Forest patch mean area (hectares) | 25.02 | 24.11 | -0.91 | 25.02 | 0.00 | 24.39 | -0.63 | 24.79 | -0.23 | 24.92 | -0.10 |
| Forest patch area median (hectares) | 1.77 | 1.62 | -0.15 | 1.77 | 0.00 | 1.65 | -0.12 | 1.71 | -0.06 | 1.72 | -0.05 |
| Susquehanna County | | | | | | | | | | | |
| Number of patches | 2,069 | 2,225 | 156 | 2,102 | 33 | 2,076 | 7 | 2,074 | 5 | 2,190 | 121 |
| Forest patch mean area (hectares) | 67.08 | 62.29 | -4.79 | 65.98 | -1.10 | 66.85 | -0.23 | 66.91 | -0.17 | 63.33 | -3.75 |
| Forest patch area median (hectares) | 0.66 | 0.64 | -0.02 | 0.65 | -0.01 | 0.65 | -0.01 | 0.65 | -0.01 | 0.64 | -0.02 |

Figure 11 illustrates the spatial distribution of the change in the number of forest patches by watershed. Note the relation between disturbance and the change in the number of forest patches. The increase of more than 40 forest patches in some watersheds indicates an increasingly fragmented landscape with habitat implications for many species.

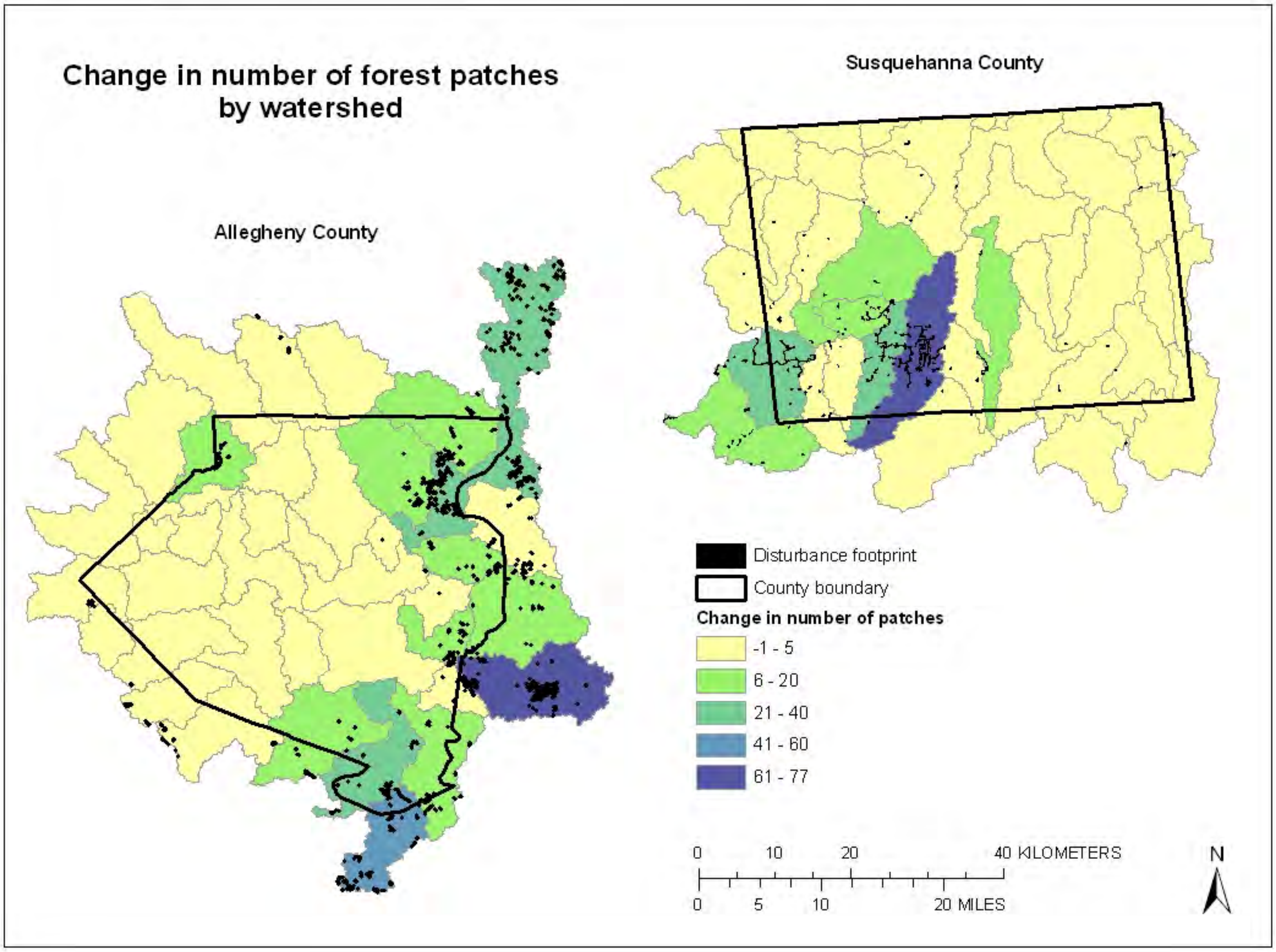

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing the increasing fragmentation in Allegheny and Susquehanna Counties, Pennsylvania. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

## Interior and Edge Forest

Forest condition (interior and edge) is another way to evaluate the state of the forest. In particular, interior forest is subject to more rapid decline than other segments of the forest. Table 6 shows the change in interior forest and edge forest based on natural gas resource development and the types of natural gas extraction infrastructure. Figures 12 and 13, respectively, illustrate the spatial distribution by watershed of change in percent interior forest and the spatial distribution of change in percent edge forest. The results indicate the following changes occurred based on 2004–2010 natural gas development:

- Allegheny County lost 0.07 percent forest (134.6 ha), which contributed to a 0.26 percent loss of interior forest (500.2 ha) and a gain of 0.14 percent in edge forest (250.1 ha). Non-Marcellus site development was the major contributor to forest loss.
- Susquehanna County lost 0.09 percent forest (194.3 ha), which contributed to a 0.22 percent loss of interior forest (453.7 ha) and a gain of 0.10 percent in edge forest (216.1 ha). Marcellus site development and pipeline construction were the major contributors to forest loss.
- The metrics suggest that the interior forest loss is two to three times that of the overall forest loss, and the gain in edge forest equals the loss of forest.

**Table 6.** Change in percent Interior forest and percent edge forest by county for 2001 (original land cover) and as updated for natural gas development disturbance (2004–2010).

[Note: Categories are not mutually exclusive. MS, Marcellus Shale site; non-MS, non-Marcellus Shale site]

| Distribution statistics | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Allegheny County | | | | | | | | | | | |
| Number of patches | 3,177 | 3,291 | 114 | 3,177 | 0 | 3,256 | 79 | 3,205 | 28 | 3,190 | 13 |
| Percent forest | 42.08 | 42.01 | -0.07 | 42.08 | -0.00 | 42.03 | -0.05 | 42.05 | -0.03 | 42.08 | -0.00 |
| Percent interior forest | 21.59 | 21.33 | -0.26 | 21.58 | -0.01 | 21.41 | -0.18 | 21.48 | -0.11 | 21.58 | -0.01 |
| Percent edge forest | 14.77 | 14.91 | 0.14 | 14.77 | 0.00 | 14.86 | 0.11 | 14.83 | 0.06 | 14.77 | 0.00 |
| Susquehanna County | | | | | | | | | | | |
| Number of patches | 2,069 | 2,225 | 156 | 2,102 | 33 | 2,076 | 7 | 2,074 | 5 | 2,190 | 121 |
| Percent forest | 64.99 | 64.90 | -0.09 | 64.94 | -0.05 | 64.99 | -0.00 | 64.99 | -0.00 | 64.95 | -0.05 |
| Percent interior forest | 46.33 | 46.11 | -0.22 | 46.23 | -0.10 | 46.31 | -0.02 | 46.31 | -0.02 | 46.17 | -0.16 |
| Percent edge forest | 13.81 | 13.91 | 0.10 | 13.85 | 0.04 | 13.81 | 0.00 | 13.82 | 0.01 | 13.90 | 0.09 |

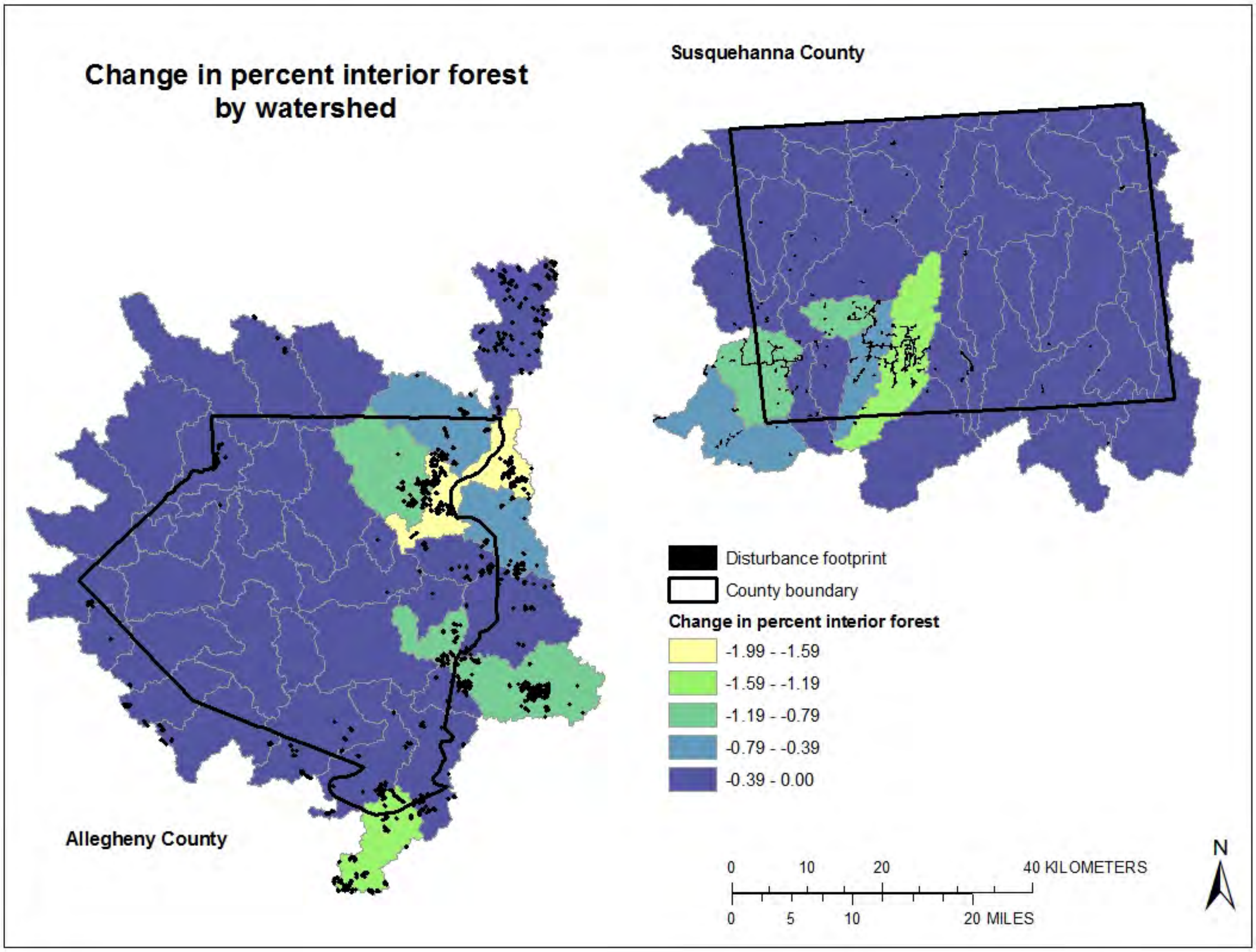

**Figure 12.** Change in percent interior forest by watershed in Allegheny and Susquehanna Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

## Conclusion

The results presented here show how natural gas extraction in Pennsylvania is affecting the landscape configuration. Agricultural and forested areas are being converted to natural gas extraction disturbance. The disturbance and effects of both Marcellus and non-Marcellus development are clearly different over both counties in that Susquehanna County has very little non-Marcellus development, but it is important to note that the combined effect of both activities is substantial.

The fractal dimension, contagion, and dominance were reported based on recommendations of O'Neill and others (1997); however, they do not appear to be important in these counties. They may be of greater importance for other counties and are reported here for consistency.

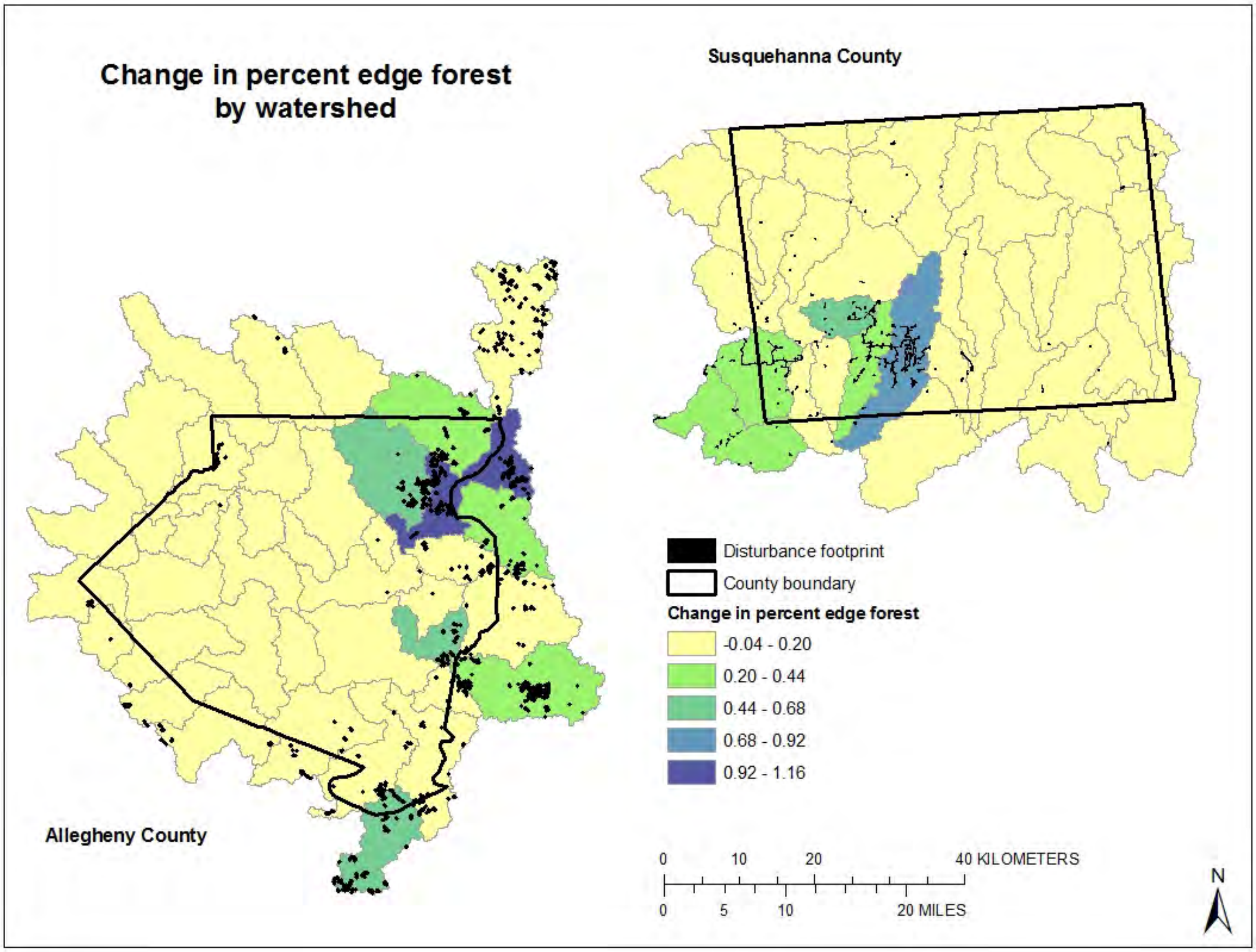

**Figure 13.** Change in percent of edge forest by watershed in Allegheny and Susquehanna Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

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# Landscape Consequences of Natural Gas Extraction in Fayette and Lycoming Counties, Pennsylvania, 2004–2010

By E.T. Slonecker, L.E. Milheim, C.M. Roig-Silva, A.R. Malizia, and B.H. Gillenwater

Open-File Report 2013–1119

**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
SALLY JEWELL, Secretary

**U.S. Geological Survey**
Suzette M. Kimball, Acting Director

U.S. Geological Survey, and reprinted: 2013

Suggested citation:
Slonecker, E.T., Milheim, L.E., Roig-Silva, C.M., Malizia, A.R., and Gillenwater, B.H., 2013, Landscape consequences of natural gas extraction in Fayette and Lycoming Counties, Pennsylvania, 2004–2010: U.S. Geological Survey Open File Report 2013–1119, 35 p.

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# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Area | |
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

# Landscape Consequences of Natural Gas Extraction in Fayette and Lycoming Counties, Pennsylvania, 2004–2010

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## Abstract

Increased demands for cleaner burning energy, coupled with the relatively recent technological advances in accessing unconventional hydrocarbon-rich geologic formations, have led to an intense effort to find and extract natural gas from various underground sources around the country. One of these sources, the Marcellus Shale, located in the Allegheny Plateau, is currently undergoing extensive drilling and production. The technology used to extract gas in the Marcellus Shale is known as hydraulic fracturing and has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on water resources. Nonetheless, development of natural gas extraction wells in the Marcellus Shale is only part of the overall natural gas story in this area of Pennsylvania. Conventional natural gas wells, which sometimes use the same technique, are commonly located in the same general area as the Marcellus Shale and are frequently developed in clusters across the landscape. The combined effects of these two natural gas extraction methods create potentially serious patterns of disturbance on the landscape. This document quantifies the landscape changes and consequences of natural gas extraction for Fayette County and Lycoming County in Pennsylvania between 2004 and 2010. Patterns of landscape disturbance related to natural gas extraction activities were collected and digitized using National Agriculture Imagery Program (NAIP) imagery for 2004, 2005/2006, 2008, and 2010. The disturbance patterns were then used to measure changes in land cover and land use using the National Land Cover Database (NLCD) of 2001. A series of landscape metrics is also used to quantify these changes and is included in this publication.

## Introduction: Natural Gas Extraction

The need for cleaner burning energy, coupled with the relatively recent technological advances in accessing hydrocarbon-rich geologic formations, has led to an intense effort to find and extract natural gas from various underground sources around the country. One of these formations, the Marcellus Shale, is currently the target of extensive drilling and production in the Allegheny Plateau. Marcellus Shale generally extends from New York to West Virginia as shown in figure 1 (Coleman and others, 2011). Coleman and others (2011) defined assessment units (AU) of Marcellus Shale production based on the geology of the region.

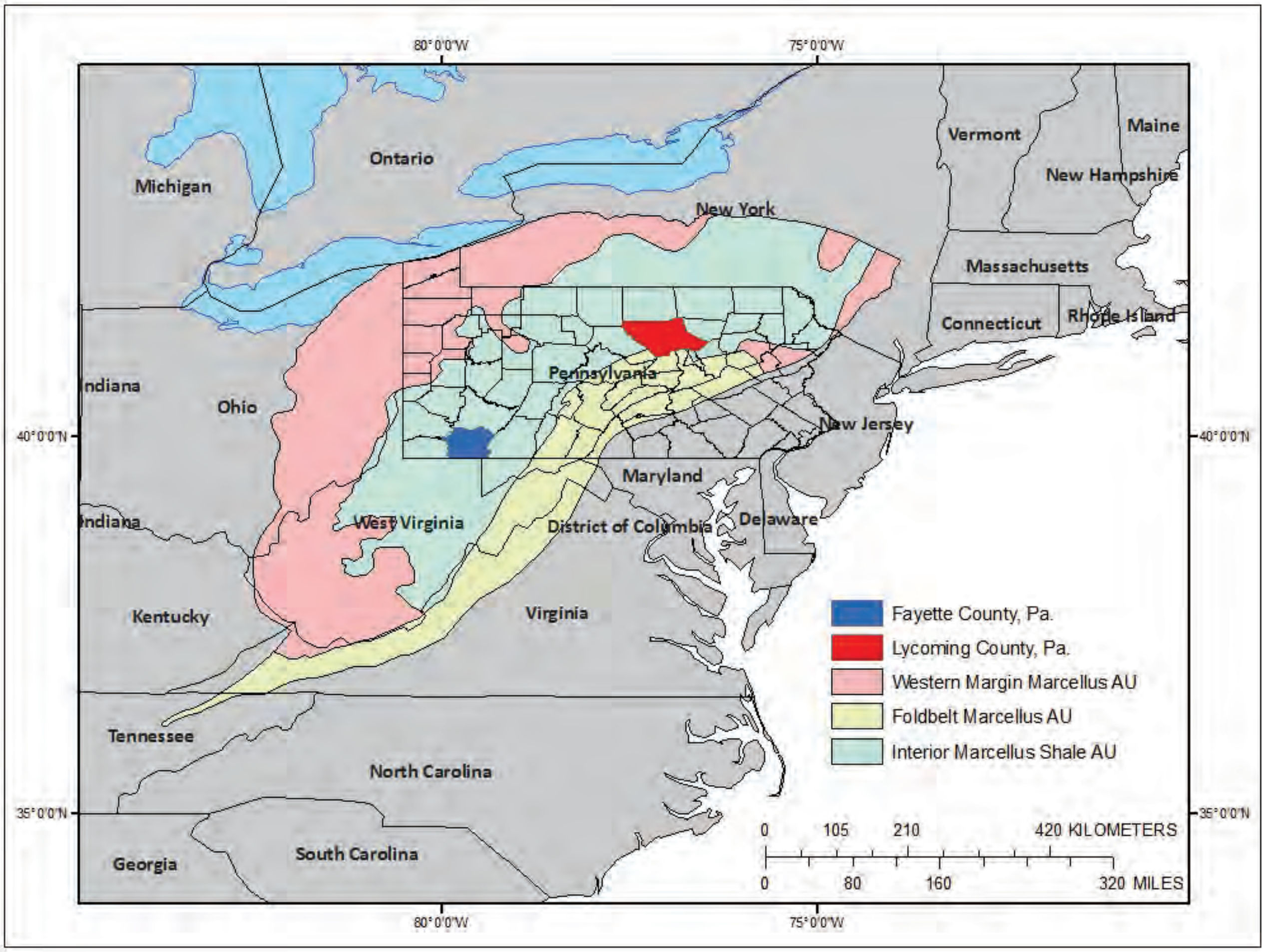

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus Shale AU is expected to be a major production area for natural gas (Coleman and others, 2011). Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S*. Geological Survey, 2011a)].

The overall landscape effects of natural gas development have been considerable. Over 9,600 Marcellus Shale gas drilling permits and over 49,500 non-Marcellus Shale permits have been issued from 2000 to 2011 in Pennsylvania (Pennsylvania Department of Environmental Protection, 2011) and over 2,300 Marcellus Shale permits in West Virginia (West Virginia Geological and Economic Survey, 2011), with most of the development activity occurring since 2005.

The Marcellus Shale is generally located 600 to 3,000 meters (m) below the land surface (Coleman and others, 2011). Gas and petroleum liquids are produced with a combination of vertical and horizontal drilling techniques, coupled with a process of hydraulically fracturing the shale formation, known as "fracking," which releases the natural gas.

The hydraulic-fracturing process has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on groundwater and drinking-water resources.

However, with all of the development of natural gas wells in the Marcellus Shale it is only part of the overall natural gas story in this area. Conventional natural gas wells are often located in the same general area as the Marcellus Shale. The conventional wells are much shallower and less productive and are often located in clusters that cover large areas of the landscape with nearly 60,000 total gas wells established. Both types of well may affect a given area. With the accompanying areas of disturbance, well pads, new roads, and pipelines from both types of natural gas wells, the effect on the landscape is often dramatic. Figure 2 shows a pattern of landscape change from forest to forest interspersed with gas extraction infrastructure. These landscape effects have consequences for the ecosystems, wildlife, and human populations that are collocated with natural gas extraction activities. This document examines the landscape consequences of gas extraction for two areas of current Marcellus Shale and non-Marcellus Shale natural gas extraction activity.

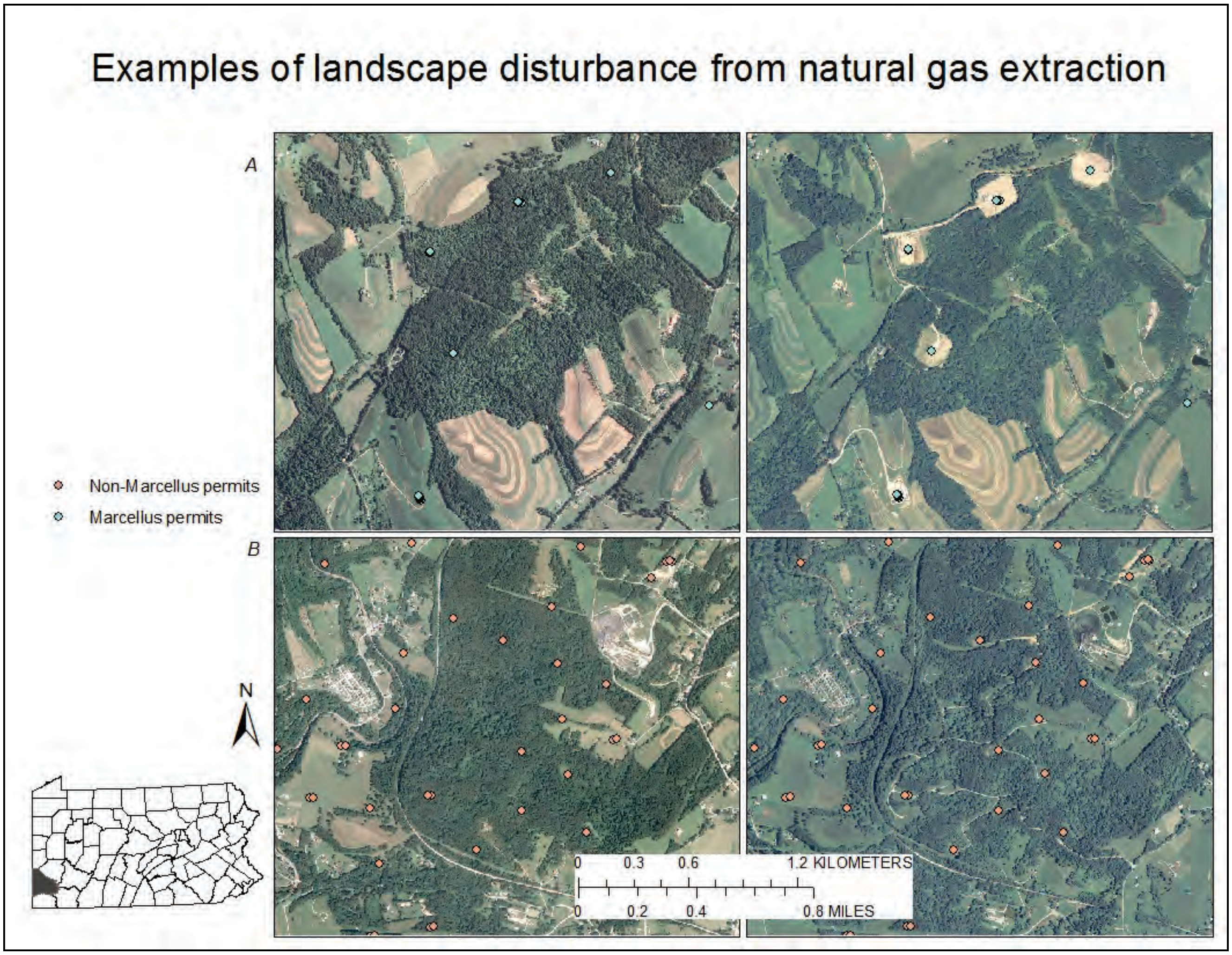

**Figure 2.** Example of forested landscapes from Washington County, Pennsylvania showing the spatial effects of roads, well pads, and pipelines related to (a) Marcellus Shale and (b) Conventional natural gas development. Inset shows the location of the images. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S*. Geological Survey, 2011a)].

## Location

This assessment of landscape effects focuses on two counties, Fayette County and Lycoming County in Pennsylvania, within the Marcellus Shale area of development known as the "Marcellus Shale Play" or the Interior Marcellus Shale AU. These counties were chosen for their position adjacent to a "sweet spot" of exceptionally productive Marcellus Shale (Stevens and Kuuskraa, 2009). Figure 3 identifies the selected counties in relation to the Interior Marcellus Shale AU and the distribution of Marcellus and non-Marcellus gas extraction permits granted by Pennsylvania.

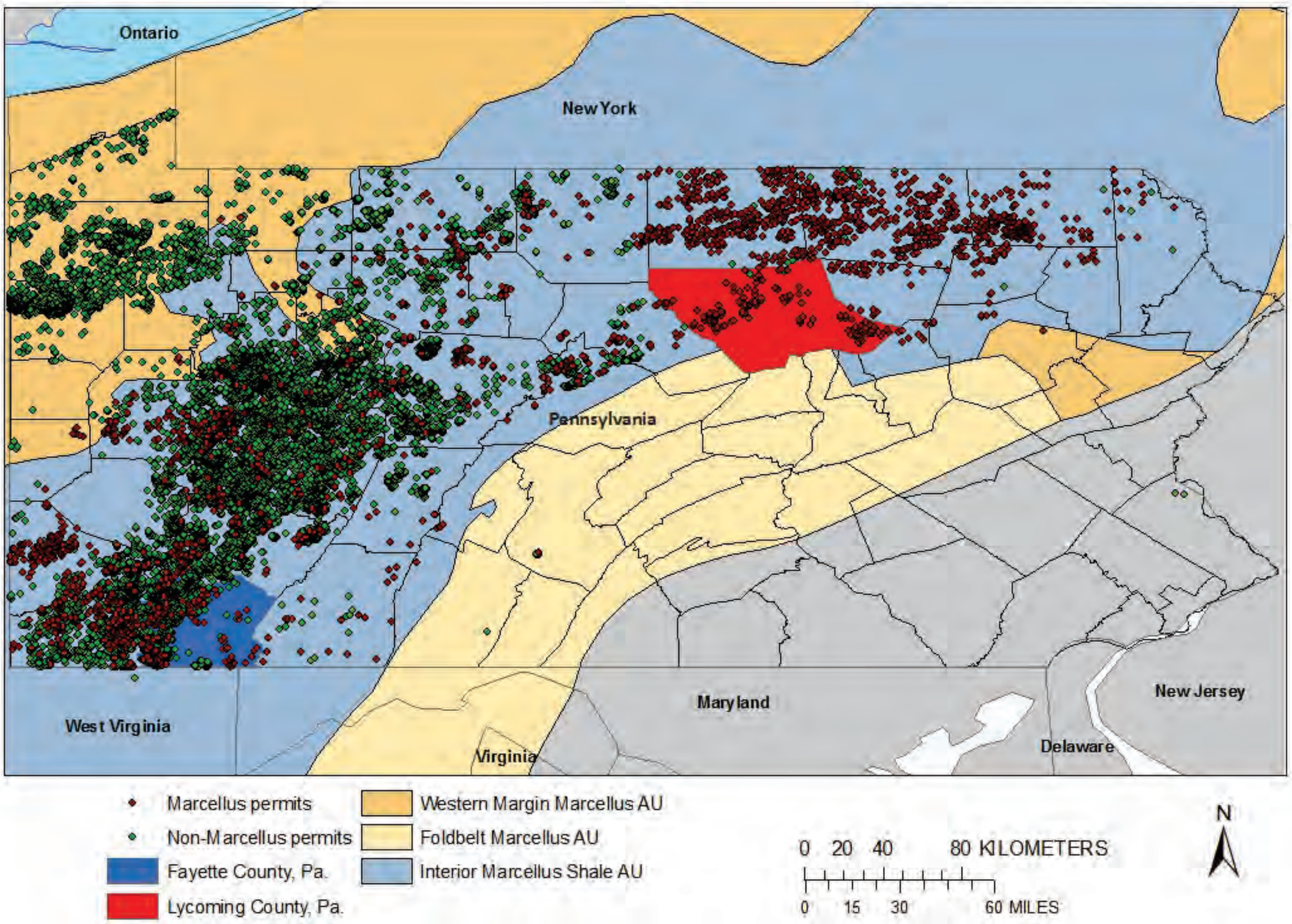

**Figure 3.** The distribution of Marcellus and non-Marcellus natural gas permits issued between 2004 and 2010 within Pennsylvania, the focal counties of Fayette and Lycoming, and their relation to the interior Marcellus Shale assessment unit. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

## The Biogeography of Pennsylvania Forests

Forests are a critical land cover in Pennsylvania. Prior to the European settlements, Pennsylvania was almost completely forested and even today, with modern agriculture, urban growth and population growth, Pennsylvania is still roughly 60 percent forested. Pennsylvania forests of the 17th century were diverse but were dominated by beech and hemlock, which composed 65 percent of the total forest

(Pennsylvania Department of Conservation and Natural Resources, 2011). In the late 19th century, Pennsylvania became the country's leading source of lumber, and a number of products, from lumber to the production of tannic acid, were generated from the forestry industry (Pennsylvania Department of Conservation and Natural Resources, 2011). By the early 20th century, most of Pennsylvania's forests had been harvested. Soon after most of the trees were felled, wildfires, erosion, and flooding became prevalent, especially in the Allegheny Plateau region (Pennsylvania Parks and Forests Foundation, 2010).

The 20th century saw resurgence in Pennsylvania forests. The Weeks Act of 1911 authorized the Federal purchase of forest land on the headwaters of navigable rivers to control the flow of water downstream and act as a measure of flood control for the thriving steel industry of Pittsburgh. Slowly, the forests began to grow back but with a vastly different composition, this time composed of black cherry, red maple, and sugar maple species (Pennsylvania Parks and Forests Foundation, 2010). For the most part, except for a very few isolated areas in north central Pennsylvania and some State parks, the majority of forest cover is currently of the new composition and not of virgin forest. Figure 4 shows that today the concentrations of forests in Pennsylvania are highest in the central and north-central parts of the State, which is also the main area of hydraulic-fracturing activity in the Marcellus Shale.

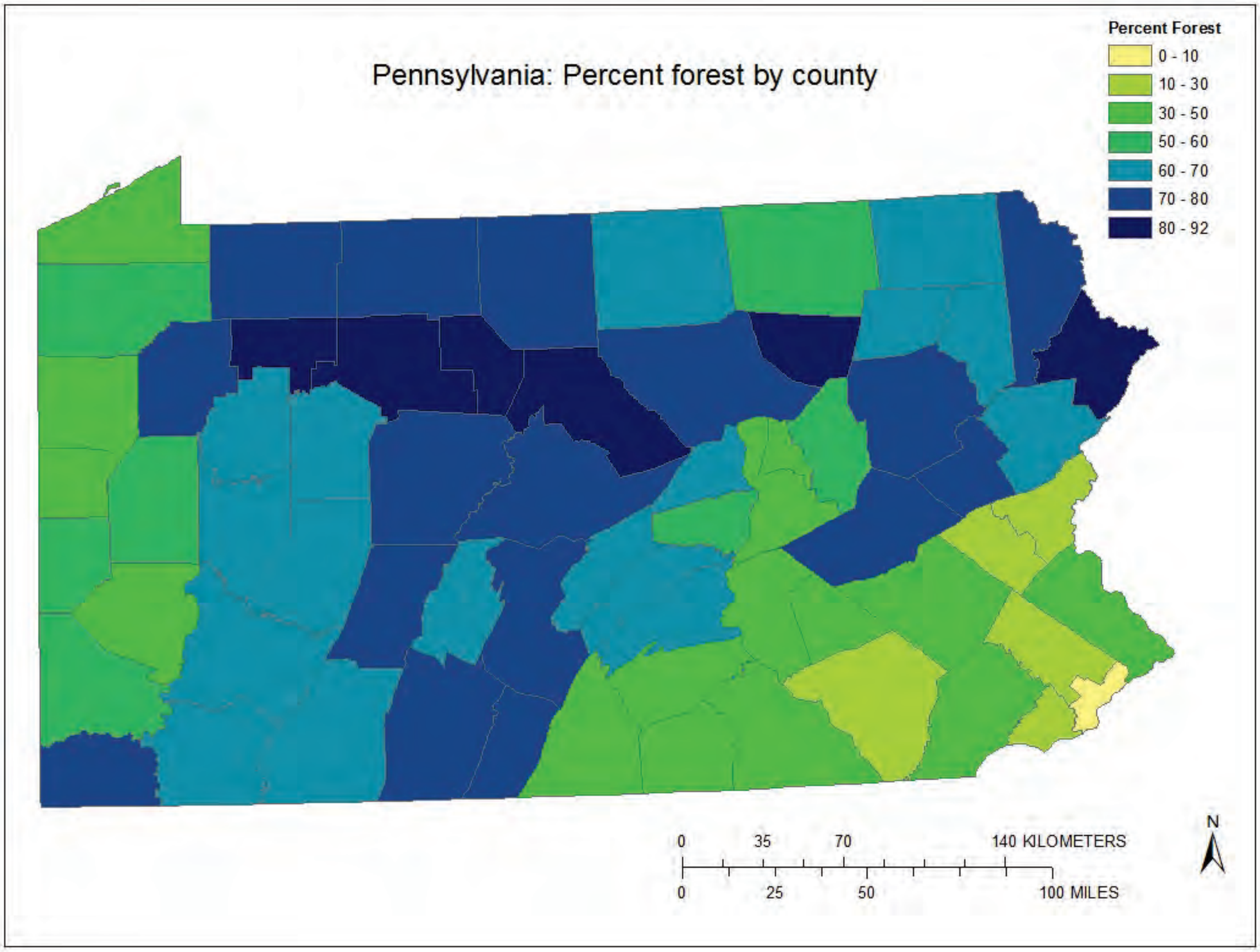

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Data. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

Pennsylvania forests provide critical habitat to a number of plant and animal species. Plant species include the sugar maple, the eastern redcedar, and evergreens that produce berries in the winter. There were a number of animal species that have been eradicated from the region, such as elk, moose, North American cougar, bison, and grey wolf (Nilsson, 2005). Today, animal species range from the more commonly found animals, such as skunks to flying squirrels, and multiple different varieties of snakes and bats. However, a diverse population of birds depends on the forests for survival. In the State of Pennsylvania, there are 394 different bird species that are native, including endangered species, such as the piping plover (Gross, 2005).

## Key Research Questions

An important aspect of this research was to quantify the level of disturbance in terms of land use and land cover change by specific disturbance category (well pads, roads, pipelines, and so forth). This quantification was accomplished by extracting the signatures of disturbance from high-resolution aerial images and then computing landscape metrics in a geographic information system (GIS) environment.

This research and monitoring effort focused on answering the following key research questions:

- What is the level of overall disturbance attributed to gas exploration and development activities and how has this changed over time?
- What are the structural components (land cover classes) of this change and how much change can be attributed to each class?
- How has the disturbance associated with natural gas exploration and development affected the structure, pattern, and process of key ecosystems, especially forests, within the Marcellus Shale Play?
- How will the disturbance stressors affect ecosystem structure and function at a landscape and watershed scale?

## Landscape Metrics and a Landscape Perspective

An important and sometimes overlooked aspect of contemporary gas exploration activity is the geographic profile and spatial arrangement of these activities on the land surface. The function of ecosystems and the services they provide are due in large part to their spatial arrangement on the landscape. Energy exploration and development represents a specific form of land use and land cover change (LULCC) activity that substantially alters certain critical aspects of the spatial pattern, form, and function of landscape interactions.

Changes in land use and land cover affect the ability of ecosystems to provide essential ecological goods and services, which, in turn, affect the economic, public health, and social benefits that these ecosystems provide. One of the great challenges for geographic science is to understand and calibrate the effects of LULCC and the complex interaction between human and biotic systems at a variety of natural, geographic, and political scales (Slonecker and others, 2010).

Changes in land use and land cover, such as the disturbance and the landscape effects of energy exploration, are currently occurring at a relatively rapid pace that is prompting immediate scientific focus and attention. Understanding the dynamics of land surface change requires an increased understanding of the complex nature of human-environmental systems and requires a suite of scientific tools that include traditional geographic data and analysis methods, such as remote sensing and GIS, as well as innovative approaches to understanding the dynamics of complex natural systems (O’Neill and others, 1997; Turner, 2005; Wickham and others, 2007). One such approach that has gained much recent scientific attention is the landscape indicator, or landscape assessment, approach, which has been developed within the science of landscape ecology (O’Neill and others, 1997).

Landscape assessment utilizes spatially explicit imagery; GIS data on land cover, elevation, roads, hydrology, vegetation; and in situ sampling results to compute a suite of numerical indicators known as **landscape metrics** to assess ecosystem condition. Landscape analysis is focused on the relation between pattern and process and broad-scale ecological relationships such as habitat, conservation, and sustainability. Landscape analysis necessarily considers both biological and socioeconomic issues and relationships. This research explores these relationships and their potential effect on various ecosystems and biological endpoints within the context of natural gas exploration.

The landscape assessment presented here is based largely on the framework outlined in O’Neill and others (1997). Many landscape metrics can be computed and utilized for some analytical purpose. However, it has been shown by several researchers (Riitters and others, 1995; Wickham and Riitters, 1995; Wickham and others, 1997) that many of these metrics are highly correlated, sensitive to misclassification and pixel size, and, to some extent, questionable in terms of additional information value. The key landscape concepts and metrics reported here are discussed below. The actual formulae used to compute these specific metrics can be found in software documentation for FRAGSTATS (McGarigal and others, 2002) and Analytical Tools Interface for Landscape Assessments (ATtILA) (Ebert and Wade, 2004). Computation details for percent interior forest and percent edge forest are documented by Riitters and others (2000).

The concept of landscape metrics, sometimes called landscape indices, is derived from the field of landscape ecology and is rooted in the realization that pattern and structure are important components of ecological process. Landscape metrics are spatial/mathematical indices that allow the objective description of different aspects of landscape structures and patterns (McGarigal and others, 2002). They characterize the landscape structure and various processes at both landscape and ecosystem levels. Metrics such as average patch size, fragmentation, and interior forest dimension capture spatial characteristics of habitat quality and potential change effects on critical animal and vegetation populations.

Two different geostatistical landscape analysis programs were used to measure the landscape metrics presented in this report. FRAGSTATS (University of Massachusetts, Amherst, Mass.) is a spatial pattern analysis program for quantifying numerous landscape metrics and their distribution, and is available at: *http://www.umass.edu/landeco/research/fragstats/fragstats.html* (McGarigal and others, 2002). ATtILA (U.S. Environmental Protection Agency (USEPA), Las Vegas, Nev.) is an Esri (Environmental Systems Research Institute, Redlands, Calif.) Arcview 3.x extension that computes a number of landscape, riparian, and watershed metrics and is available at: *http://www.epa.gov/esd/land-sci/attila/* (Ebert and Wade, 2004). Metrics are presented here at the county level and mapped at the watershed level defined by 12-digit Hydrologic Unit Codes (HUC-12).

## Disturbance

Disturbance is a key concept in a landscape analysis approach and in ecology in general. Gas development activities create a number of disturbances across a heterogeneous landscape. In landscape analysis, disturbances are discrete events in space and time that disrupt ecosystem structure and function and change resource availability and the physical environment (White and Pickett, 1985; Turner and others, 2001). When natural or anthropogenic disturbance occurs in natural systems, it generally alters abiotic and biotic conditions that favor the success of different species, such as opportunistic invasive species over predisturbance organisms. Natural gas exploration and development results in spatially explicit patterns of landscape disturbance involving the construction of well pads and impoundments, roads, pipelines, and disposal activities that have structural impacts on the landscape (fig. 2).

Development of multiple sources of natural gas results in increased traffic from construction, drilling operations (horizontal and vertical), hydraulic fracturing, extraction, transportation, and maintenance activities. The presence of humans, construction machinery, infrastructure (for example, well pads and pipelines), roads, and vehicles alone may substantially impact flora and fauna. Increased traffic, especially rapid increases on roads that have historically received little activity, can have detrimental impacts on animal and plant populations (Gibbs and Shriver, 2005). Forest loss as a result of disturbance, fragmentation, and edge effects has been shown to negatively affect water quality and runoff (Wickham and others, 2008), impact species, alter biosphere-atmosphere dynamics that could contribute to climate change (Hayden, 1998; Bonan, 2008), and affect the long-term survival of the forest itself (Gascon and others, 2007).

The initial step of landscape analysis is to determine the spatial distribution of disturbance to identify relative hotspots of activity. This knowledge allows greater focus to be placed on specific locations. Disturbance in this report is presented as both graphic files and tables of summary statistics.

Figure 5 provides an example of the distribution of natural gas extraction in Bradford County, Pennsylvania, and it also shows how that disturbance is placed with respect to the local land cover.

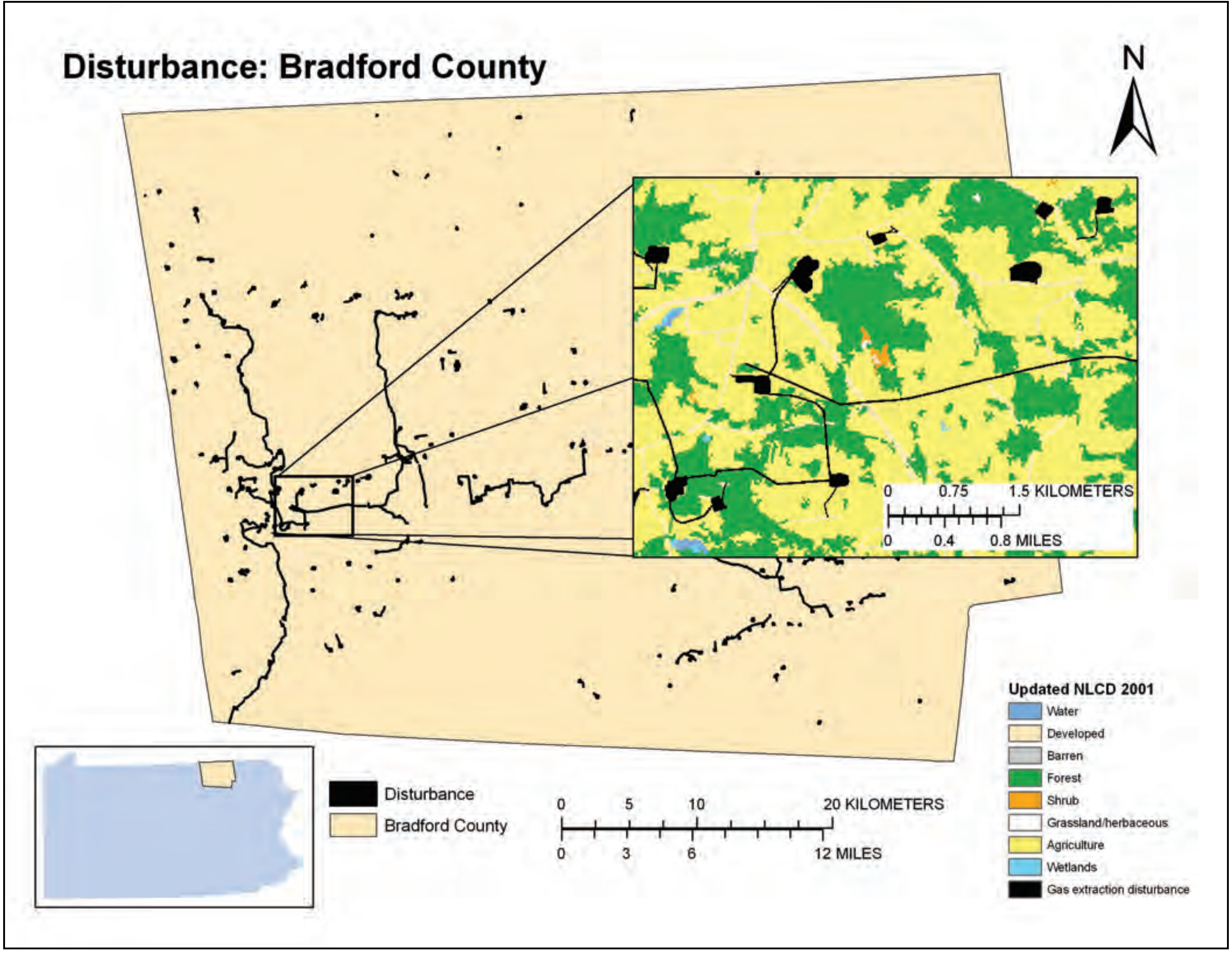

**Figure 5.** Example of a natural gas disturbance footprint from Bradford County, Pennsylvania, embedded within the National Land Cover Dataset (NLCD) 2001. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

## Forest Fragmentation

Forest fragmentation is the alteration of forest into smaller, less functional areas. Fragmentation of forest and habitat is a primary concern resulting from current gas development. Habitat fragmentation occurs when large areas of natural landscapes are intersected and subdivided by other, usually anthropogenic, land uses leaving smaller patches to serve as habitat for various species. As human activities increase, natural habitats, such as forests, are divided into smaller and smaller patches that have a decreased ability to support viable populations of individual species, particularly those in large ranges adapted to interior forest conditions. Habitat loss and forest fragmentation can be major threats to biodiversity, although research on this topic is inconclusive (With and Pavuk, 2011).

Although many human and natural activities result in habitat fragmentation, gas exploration and development activity can be extreme in their effect on the landscape. The development of numerous secondary roads and pipeline networks crisscrosses and subdivides habitat structure.

Landscape disturbance associated with shale-gas development infrastructure directly alters habitat through loss, fragmentation, and edge effects, which in turn alter the flora and fauna dependent on that habitat. The fragmentation of habitat is expected to amplify the problem of total habitat area reduction for wildlife species, as well as contribute to habitat degradation. Fragmentation alters the landscape by creating a mosaic of spatially distinct habitats from originally contiguous habitat, resulting in smaller patch size, greater number of patches, and decreased interior to edge ratio (Lehmkuhl and Ruggiero, 1991; Dale and others, 2000). Fragmented habitats generally result in detrimental impacts to flora and fauna caused by increased mortality of individuals moving between patches, lower recolonization rates, and reduced local population sizes (Fahrig and Merriam, 1994). The remaining patches may be too small, isolated, and possibly too influenced by edge effects to maintain viable populations of some species. The rate of landscape change can be more important than the amount or type of change because the temporal dimension of change can affect the probability of recolonization for endemic species, which are typically restricted by their dispersal range and the kinds of landscapes in which they can move (Fahrig and Merriam, 1994).

While general assumptions and hypotheses can be derived from existing scientific literature involving similar stressors, the specific impacts of habitat loss and fragmentation in the Marcellus Shale Play will depend on the needs and attributes of specific species and communities. A recent analysis of Marcellus well permit locations in Pennsylvania found that well pads and associated infrastructure (roads, water impoundments, and pipelines) required nearly 3.6 hectares (ha) (9 acres) per well pad with an additional 8.5 ha (21 acres) of indirect edge effects (Johnson, 2010). This type of extensive and long-term habitat conversion has a greater impact on natural ecosystems than activities such as logging or agriculture, given the great dissimilarity between gas-well pad infrastructure and adjacent natural areas and the low probability that the disturbed land will revert back to a natural state in the near future (high persistence) (Marzluff and Ewing, 2001). Figure 6 shows an example of the concept of the landscape metric of forest fragmentation.

## Interior Forest

Interior forest is a special form of habitat that is preferred by many plant and animal species and is defined as the area of forest at least 100 m from the forest edge (Harper and others, 2005). Interior forest is an important landscape characteristic because the environmental conditions, such as light, wind, humidity, and exposure to predators, within the interior forest are very different from areas closer to the forest edge. Interior forest habitat is related to the size and distribution of forest patches and is closely tied to the concept of forest or habitat **fragmentation**. The amount of interior forest can be dramatically affected by linear land use patterns, such as roads and pipelines, which tend to fragment land patches into several smaller patches and destroy available habitat for certain species. Figure 6 shows the general concept of increased fragmentation and reduced interior forest.

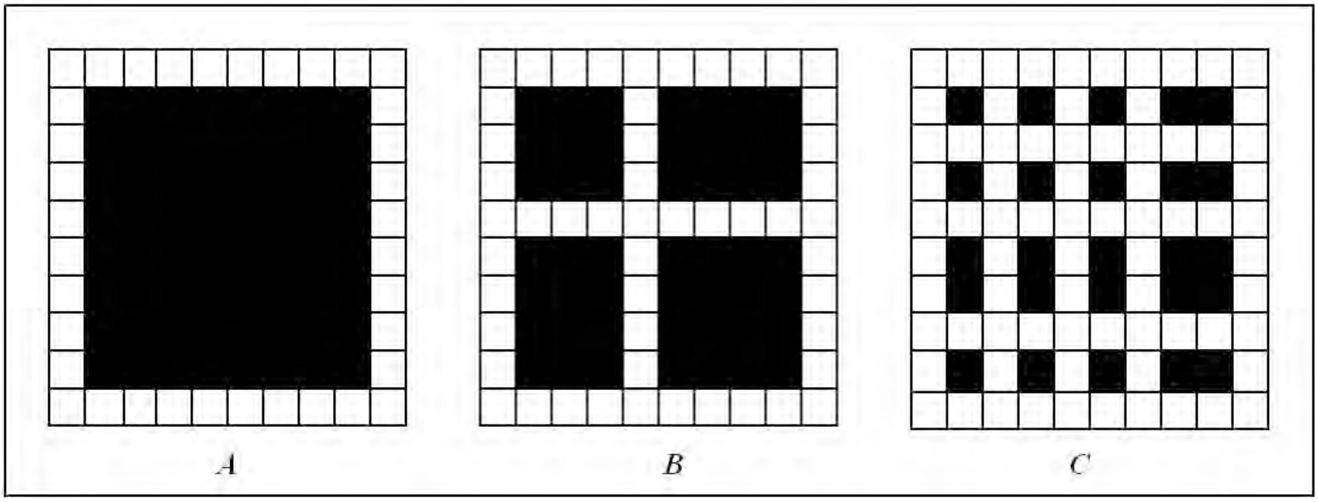

**Figure 6.** Conceptual illustration of interior forest and how this critical habitat is affected by linear disturbance. *A*, High interior area; *B*, Moderate interior area; and *C*, Low interior area (Riitters and others, 1996).

## Forest Edge

Forest edge is simply a linear measure of the amount of edge between forest and other land uses in a given area, and especially between natural and human-dominated landscapes. The influence of the two bordering communities on each other is known as the edge effect. When edges are expanded into natural ecosystems, and the area outside the boundary is a disturbed or unnatural system, the natural ecosystem can be affected for some distance in from the edge (Skole and Tucker, 1993). Edge effects are variable in space and time. The intensity of edge effects diminishes as one moves deeper inside a forest, but edge phenomena can vary greatly within the same habitat fragment or landscape (Laurance and others, 2007). Factors that might promote edge-effect variability include the age of habitat edges, edge aspect, and the combined effects of multiple nearby edges, fragment size, seasonality, and extreme weather events.

Spatial variability of edge effects may result from local factors such as the proximity and number of nearby forest edges. Plots with two or more neighboring edges, such as smaller fragment plots, have greater tree mortality and biomass loss. Edge age also influences edge effects. Over time, forest edge can be partially sealed by invasive vines and second growth underbrush, which will influence the ability of smaller tree seedlings to survive in this environment. Likewise, the matrix of adjoining vegetation plots will have a strong influence on edge effects. Forest edges adjoined by young regrowth forest provide a physical buffer from wind and light. Extreme weather events also affect the temporal variability in edge effects. Abrupt, artificial boundaries of forest fragments are vulnerable to windstorms, snow and ice, and convectional thunderstorms that can weaken and destroy exposed forest edges. Periodic droughts can also have a more pronounced effect on forest edges that are exposed to drier wind conditions and higher rates of evaporation.

## Contagion

Contagion is an indicator that measures the degree of “clumpiness” among the classes of land cover features and is related to patch size and distribution. Contagion ($0<x\leq100$, disaggregated to aggregated) expresses the degree to which adjacent pixel pairs can be found in the landscape. Figure 7 shows the general concept of contagion and gives examples of low, medium, and high contagion. Contagion is valuable because it relates an important measure of how landscapes are fragmented by

patches. Landscapes of large, less-fragmented patches have a high contagion value, and landscapes of numerous small patches have a low contagion value (McGarigal and others, 2002).

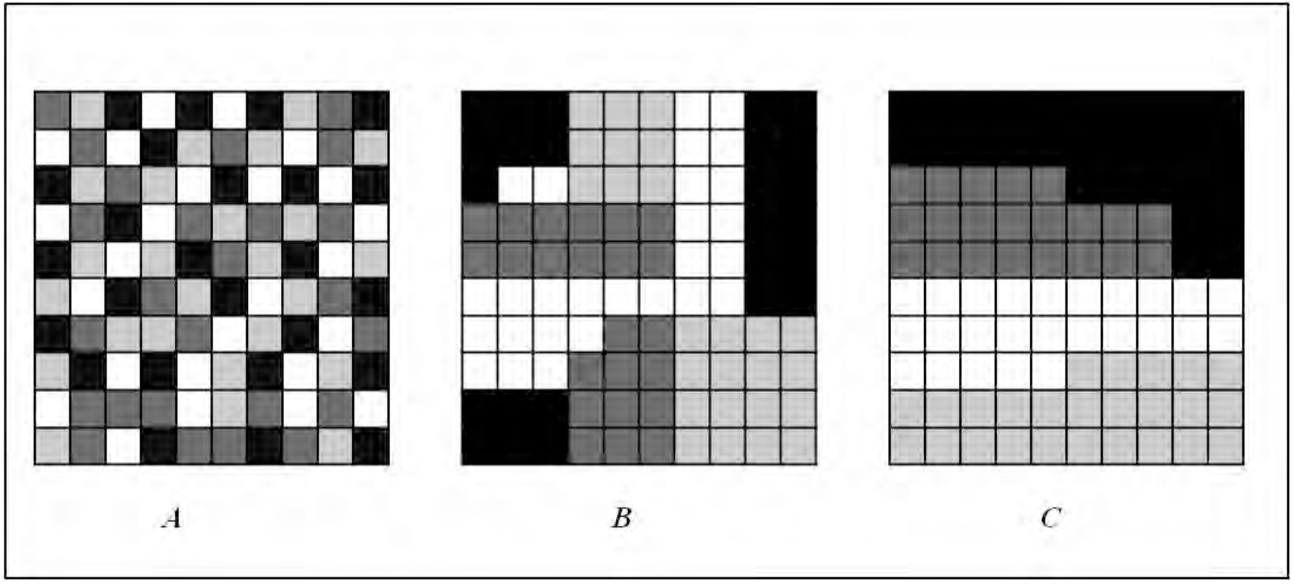

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or "clumped" to one another. *A*, Low contagion; *B*, Moderate contagion; and *C*, High contagion (after Riitters and others, 1996).

### Fractal Dimension

Fractal dimension describes the complexity of patches or edges within a landscape and is generally related to the level of anthropogenic influence in a landscape. Fractal dimension generally measures the perimeter-to-area proportional relationship of a patch. Human land uses tend to have simple, circular, or rectangular shapes, of low complexity and, therefore, low fractal dimensions. Natural land covers have irregular edges, complex arrangements and, therefore, higher fractal dimensions. The fractal dimension index ranges between 1 and 2, with 1 indicating high human influences in the landscape and 2 with natural patterns and low human influence (McGarigal and others, 2002).

### Dominance

Dominance is a measure of the relative abundance of different patch types, typically emphasizing either relative evenness or equity in the distribution. Dominance is high when one land cover type occupies a relatively large area of a given landscape and is low when land cover types are evenly distributed. Dominance is the complement to evenness, which is sometimes used as an alternative measure of the relative area of one land cover type over others in the landscape.

Although there are many metrics associated with dominance, here we report on a simple landscape metric—the Simpson's Evenness Index, which is a measure of the proportion of the landscape occupied by a patch type divided by the total number of patch types in the landscape (McGarigal and others, 2002).

## Methodology: Mapping and Measuring Disturbance Effects

High-resolution aerial imagery for each of four timeframes—2004, 2005/2006, 2008, and 2010—were brought into a geographic information system (GIS) database, along with additional geospatial data on Marcellus and non-Marcellus well permits and locations, administrative boundaries, ecoregions, and geospatial information on the footprint of the Marcellus Shale Play in Pennsylvania. The imagery was examined for distinct signs of disturbance related to oil and gas drilling and development as described below. The observable features were manually digitized as line and polygon features in a GIS format. The polygons and line features were processed and aggregated into a raster mask used to update existing land cover data. Summary statistics for each county were developed and reported. Detailed landscape metrics were calculated and mapped over HUC-12 watersheds within or intersecting the boundary of each county. All metrics are calculated on the 2001 NLCD and the 2001 NLCD as updated by disturbance collected from 2004 to 2010 to isolate the natural gas extraction disturbance effects.

## Data

### Sources

High-resolution aerial imagery (1 m) from the National Agricultural Imagery Program (NAIP) was downloaded for each timeframe. NAIP imagery is flown to analyze the status of agricultural lands approximately every 2 to 3 years (U.S. Department of Agriculture, Farm Service Agency, 2011). The NAIP imagery consists of readily available, high-resolution data that are suitable for detailed analysis of the landscape. NAIP imagery is available from the U.S. Department of Agriculture Geospatial Data Gateway Web site (U.S. Department of Agriculture, Natural Resources Conservation Service, 2011). Table 1 identifies the source imagery dates for each county and year.

**Table 1.** Acquisition dates of National Agriculture Imagery Program (NAIP) source data.

| Year | Source Imagery Dates (chronological from left to right) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Fayette County | | | | | | | | | |
| 2004 | 2004-06-27 | 2004-07-03 | 2004-07-07 | 2004-08-02 | 2004-09-01 | 2004-09-03 | 2004-09-11 | 2004-09-13 | 2004-10-06 |
| 2005 | 2005-06-23 | 2005-06-24 | 2005-09-07 | 2005-09-10 | 2005-09-11 | 2005-09-13 | 2005-09-21 | | |
| 2008 | 2008-07-15 | 2008-07-16 | 2008-07-18 | 2008-07-19 | 2008-07-29 | 2008-09-03 | | | |
| 2010 | 2010-06-08 | 2010-06-18 | 2010-06-19 | 2010-09-02 | | | | | |
| Lycoming County | | | | | | | | | |
| 2004 | 2004-06-12 | 2004-06-24 | 2004-08-23 | 2004-09-01 | 2004-09-23 | 2004-10-07 | 2004-11-06 | 2004-11-07 | |
| 2005 | 2005-06-21 | 2005-06-23 | 2005-06-24 | 2005-07-10 | 2005-07-20 | | | | |
| 2008 | 2008-08-04 | 2008-08-16 | 2008-09-01 | 2008-09-02 | 2008-09-05 | 2008-09-19 | 2008-10-07 | 2008-10-11 | |
| 2010 | 2010-06-02 | 2010-07-05 | 2010-07-07 | 2010-07-11 | 2010-09-01 | | | | |

Drilling permits for Marcellus Shale and non-Marcellus Shale natural gas were obtained from the Pennsylvania Department of Environmental Protection Permit and Rig Activity Reports for 2004–2010 (Pennsylvania Department of Environmental Protection, Office of Oil and Gas Management, 2011).

The U.S. Geological Survey (USGS) Watershed Boundary Dataset 12-digit Hydrologic Unit Code (HUC12) for Pennsylvania was downloaded from the USGS National Hydrography Dataset Web site (U.S. Geological Survey, 2011b).

The Marcellus Shale Play assessment unit boundaries were downloaded from the USGS Energy Resources Program Data Services Web site (U.S. Geological Survey, 2012).

The 2001 National Land Cover Dataset (NLCD) was acquired for use as the baseline land cover map. The NLCD is a 16-class land cover classification scheme applied consistently across the United States at a 30-m spatial resolution (Homer and others, 2007) and is released on a 5-year cycle. The 2001 NLCD was chosen as the baseline because the 2006 NLCD contained some of the landscape changes collected during this study. The NLCD may be acquired using the Multi-Resolution Land Characteristics Consortium Web site (U.S. Geological Survey, 2011c). The NLCD 2001 was resampled to 10-m-pixel size.

## Collection

These data were brought into a GIS database for spatial analysis. The imagery was examined for distinct signs of disturbance related to oil and gas drilling and development. These features include the following:

- Sites—Cleared areas related to existing permits or displaying the characteristics of a shale or conventional gas extraction site.
- Roads—Vehicular transportation corridors constructed specifically for shale or conventional gas development.
- Pipelines—New gas pipelines constructed in conjunction with one or more well pads.
- Impoundments—Manmade depressions designed to hold liquid and in support of oil and gas drilling operations.
- Other—Support areas or activities such as processing plants, storage tanks, and staging areas.

The collection of gas extraction infrastructure data was a manual process of visually examining high-resolution imagery for each county over four dates to identify and digitize (collect) changes in the land cover resulting from the development of gas extraction infrastructure. Specifically, NAIP 1-m data composited for the years 2004, 2005/2006, 2008, and 2010were examined using 2004 imagery as a baseline, identifying landscape changes that occurred after 2004.

Changes that correlated with natural gas extraction permits, appeared to be natural gas extraction related, or were in proximity to other gas extraction infrastructure were selected and digitized to the maximum extent of landscape disturbance. The focus of the data collection was on features attributable to the construction, use, and maintenance of gas extraction drill sites, processing plants, and compressor stations, as well as the center lines for new roads accessing such sites, plants, and stations, and the center lines for new pipelines used to transport the extracted gas. Figure 8 shows examples of digitized natural gas extraction features. These data were collected within shapefiles by county, using ArcGIS 10.0. One shapefile was generated for sites (polygons), one was generated for roads (lines), and one was generated for pipelines (lines). Roads and pipelines were generally buffered to 8 and 12 m, respectively, for overall area assessments. The buffered distance was selected as the average from measurement of roads and pipelines in the counties. All sites were initially classified as gas extraction related or points of interest. Points of interest were unlikely to be related to drilling, but were of potential future interest and excluded from further processing. All data collected were reviewed by another team member for concurrence and consistency.

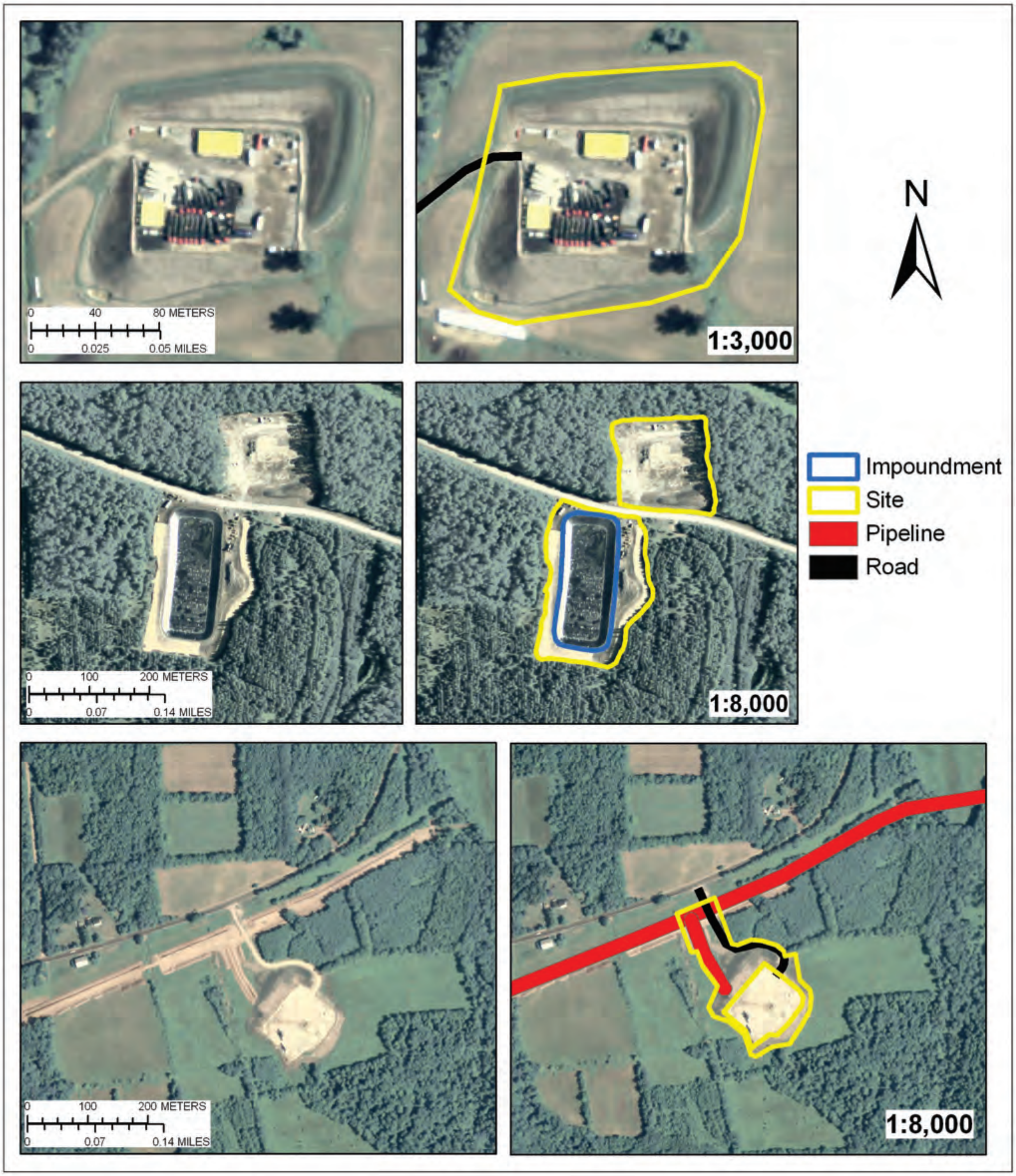

**Figure 8.** Examples of spatially explicit features of disturbance that were extracted from aerial photographs into a geographic information system (GIS) format.

## Land Cover Update

Using the collected and reviewed data, the polygons and line features were processed and aggregated into a raster format used as a mask to update existing land cover data from NLCD 2001. Figure 9 shows the processing flow to accomplish this task consistently across both counties.

Each feature within the shapefiles was compared to the permit database to determine its permit status and its area calculated. A subset of features and roads was selected by infrastructure type (all, Marcellus, non-Marcellus, other and pipelines). The selected features were then merged and internal boundaries dissolved resulting in a disturbance footprint shapefile for that county. The disturbance footprint was then rasterized (10-m-pixel size) and used to conditionally select the pixels in the resampled 2001 NLCD to reclassify as a new class: gas extraction disturbance. To consistently perform this processing, a set of models was developed using the ArcGIS ModelBuilder.

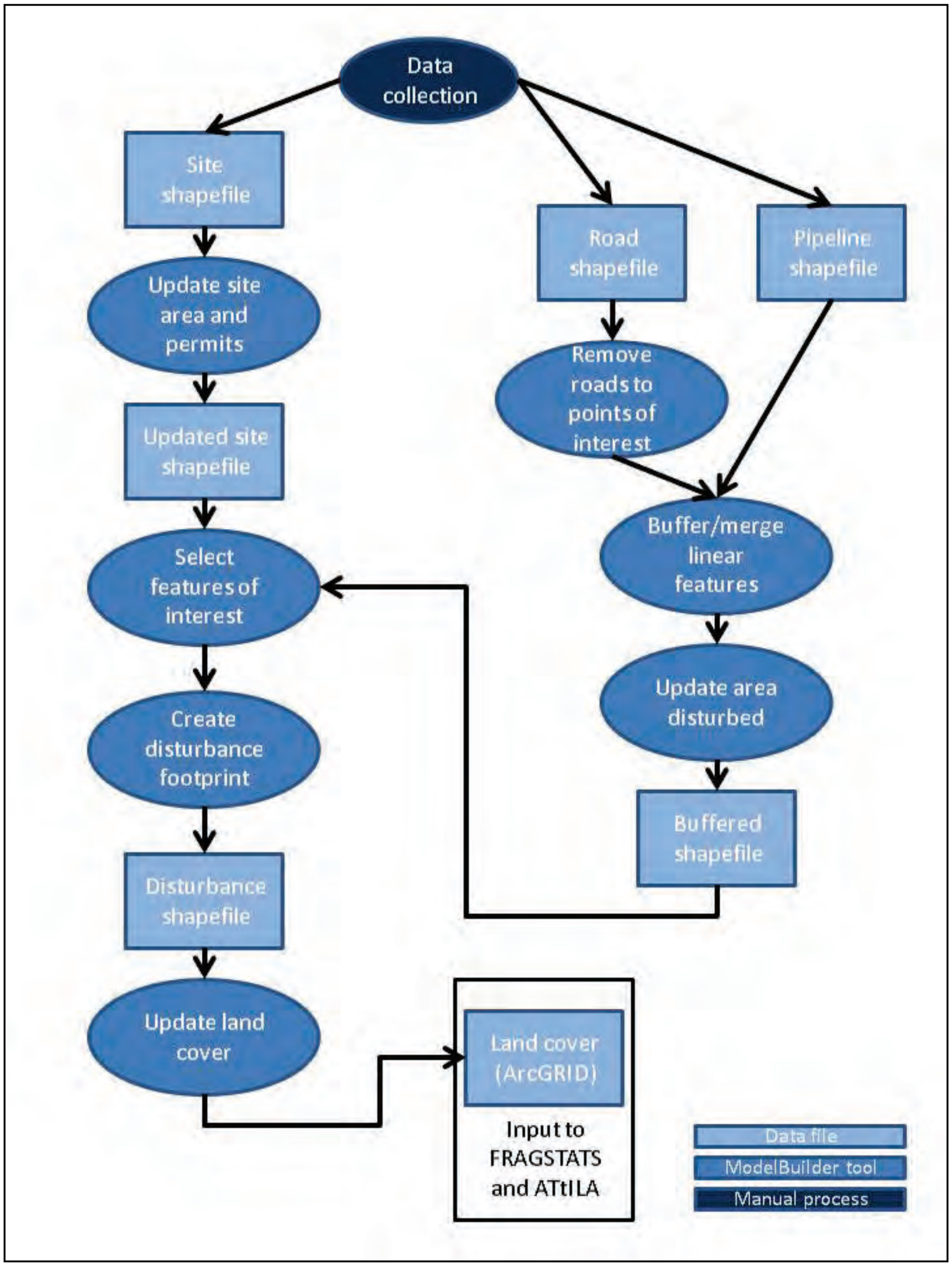

**Figure 9.** Workflow diagram for creating an updated land cover map. The workflow was implemented using ArcGIS ModelBuilder scripts to process the digitized data and embed results in the resampled NLCD 2001.

## Calculation of Landscape Metrics

Landscape-wide and land cover class fragmentation statistics for each county were developed and reported using FRAGSTATS, while land cover class-detailed statistics, forest fragmentation statistics, including patch metrics and forest condition (interior, edge, and so forth) metrics were calculated over smaller watersheds (HUC12) intersecting with the county using ATtILA. The collected statistics were then summarized, charted, and mapped for further analysis.

In addition to the summary of features noted above, a series of landscape metrics was calculated for each county based on the change related to gas development activities between 2004 and 2010. To do this, the metrics were calculated from the 2001 NLCD dataset (Homer and others, 2007). Following that calculation, the 2004–2010 cumulative spatial pattern of disturbance was digitally embedded into the 2001 NLCD dataset and the metrics were recalculated for each county.

## Results: Summary Statistics and Graphics

This section presents a summary for each county of landscape alterations from natural gas resource development, along with the ensuing change in land cover and landscape suggested by O'Neill and others (1997). These metrics are then calculated and presented based on the sources of that disturbance: Marcellus (MS) sites and roads; non-Marcellus (non-MS) (conventional) sites and roads; other infrastructure, which includes nonpermitted sites, and processing facilities and their associated roads; and pipelines and their associated roads. Nonpermitted sites are defined as disturbed areas that appear to be Marcellus or non-Marcellus gas extraction sites that do not have a permit within 250 m of the disturbance. These data are presented in tabular form with some graphic presentations provided where appropriate. Examples of the spatial distribution of selected landscape metrics are shown at the watershed level for each county. GIS data of all disturbance features are available upon request.

### Disturbed Area

Documenting the spatially explicit patterns of disturbance was one of the primary goals of this research, and this section describes the extent of disturbed land cover for Fayette and Lycoming Counties in Pennsylvania. The spatial distribution of disturbance influences the impacts of that disturbance. Figure 10 shows the distribution of disturbance within Fayette and Lycoming Counties.

In Fayette County, disturbance is occurring on the western side of the county (fig. 10). On the other hand, Lycoming County's disturbance is scattered with most of it occurring in clusters in the eastern and western edges of the county. The detailed insets in figure 10 show the disturbance footprints in the context of the surrounding land cover.

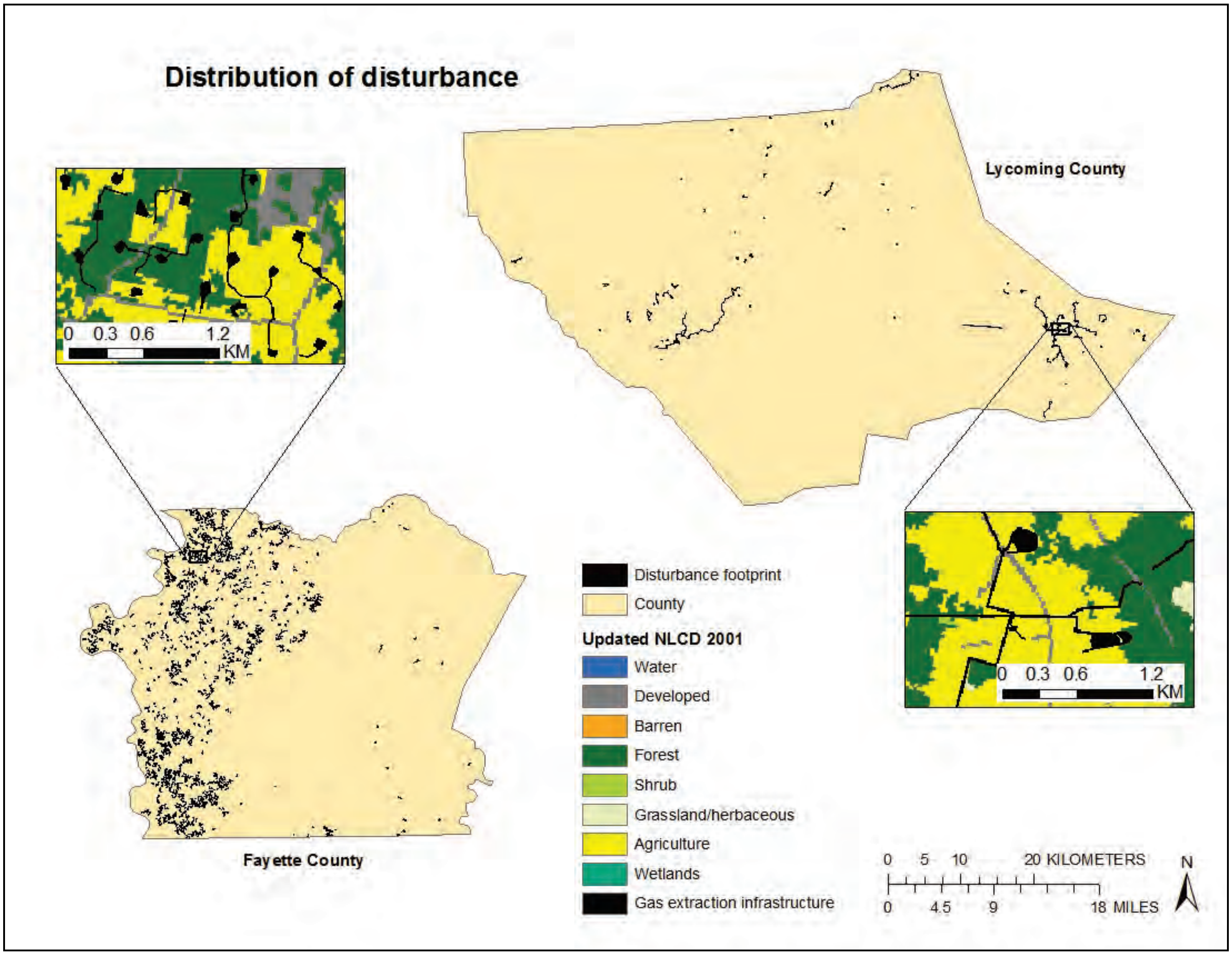

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Fayette and Lycoming Counties, Pennsylvania. Base-map data courtesy of The National Map [(*http://viewer.nationalmap.gov/viewer)* *(U.S*. Geological Survey, 2011a)].

Table 2 lists the disturbance area attributable to all sites and impoundments and their associated roads and pipelines. The disturbance area is presented first as a total disturbance for all gas extraction infrastructure, including all sites, roads, and pipelines. Total disturbance is then divided into sections: the first includes disturbance for all sites and their associated roads and the second includes disturbance for pipelines and impoundments. The disturbance area for all sites and roads is further divided into disturbance for Marcellus Shale permitted sites and roads, non-Marcellus Shale permitted sites and roads, sites lacking an identifiable permit (for example, processing facilities or incomplete permit data), and sites with permits for both Marcellus and non-Marcellus drilling , also called dual sites. Additionally, the disturbance area associated with impoundments is presented for those impoundments greater than 0.4 ha and for those less than 0.4 ha. Because land disturbance or access roads may be associated with multiple infrastructural components (for example, pipelines may cross areas also disturbed for drill sites), the values for disturbed areas and road miles within break-out categories, such as “MS sites and roads,” do not sum up to the higher level category—in this instance, “All sites and roads." The results indicate the following changes occurred based on 2004–2010 natural gas development:

- While Lycoming County is larger (~322,730 ha) than Fayette County (~206,437 ha), Fayette County has more sites, with 114 Marcellus and 1,183 non-Marcellus sites compared to 78 Marcellus and 5 non-Marcellus sites in Lycoming.
- Marcellus sites are larger than non-Marcellus sites in both counties.
- Overall, Lycoming County has nearly three times the mean acres of disturbance per site as Fayette County (2.3 ha/site compared to 0.8 ha/site, respectively) due to the dominance of the smaller non-Marcellus sites in Fayette County.
- The mean disturbed hectares for Marcellus sites were almost identical for both counties (2.9 ha/site for Fayette County and 3.0 ha/site for Lycoming County)
- Mean disturbed hectares per non-Marcellus sites were about half as large in Fayette than in Lycoming (2.3 ha/site compared to 1.1 ha/site, respectively).
- Fayette County had almost 16 times the number of other infrastructure sites that include processing and transportation facilities and nonpermitted sites as Lycoming County (234 sites and 15 sites, respectively). However, these sites were about one half the mean size (0.7 ha for Fayette County compared to 1.6 ha for Lycoming County).
- Fayette County had 6 times the amount of dual sites as Lycoming County (30 sites in Fayette County compared to 5 in Lycoming County). The disturbance associated with dual sites was included in the disturbance measures for both Marcellus and non-Marcellus sites.
- Fayette County had more total impoundments (73) than Lycoming County (52), and a larger proportion of small (<0.4 ha) impoundments (69 out of 73 and 40 out of 52 impoundments, respectively.) The relationship between small impoundments and site type is not clear. It may vary from county to county or region to region or by topography and sedimentation regulations.

**Table 2.** Cumulative amount of landscape disturbance for natural gas extraction development and infrastructure based on disturbance type from 2004 to 2010 by county.

[Note: Categories are not mutually exclusive. MS, Marcellus Shale site; non-MS, non-Marcellus Shale site; >, greater than; <, less than; ha, hectare]

| Land cover update | Count | Site only hectares | Footprint disturbed hectares | Road kilometers | Pipeline kilometers | Hectares per site | Disturbed hectares per site | Road kilometers per site |
|---|---|---|---|---|---|---|---|---|
| Fayette County (205,437 hectares) | | | | | | | | |
| All infrastructure | 1,502 | 1,161.3 | 1,765.1 | 466.9 | 3.7 | 0.8 | 1.2 | 0.3 |
| All sites and roads | 1,495 | 1,156.0 | | 465.0 | | | | 0.3 |
| MS sites and roads | 114 | 248.9 | 325.7 | 62.7 | | 2.2 | 2.9 | 0.3 |
| Non-MS sites and roads | 1,183 | 822.5 | 1,338.2 | 552.4 | | 0.7 | 1.1 | 0.3 |
| Other infrastructure/ nonpermitted sites and roads | 234 | 160.9 | 319.7 | 111.9 | | 0.7 | 1.4 | 0.4 |
| Dual sites | 30 | 72.1 | | | | | | |
| Pipelines | 2 | 9.2 | 13.5 | 5.5 | 3.7 | 4.6 | 6.7 | 0.5 |
| Impoundments (>0.4 ha) | 6 | 3.9 | | | | 0.7 | | |

**Table 2.** Cumulative amount of landscape disturbance for natural gas extraction development and infrastructure based on disturbance type from 2004 to 2010 by county.—Continued

[Note: Categories are not mutually exclusive. MS, Marcellus Shale site; non-MS, non-Marcellus Shale site; >, greater than; <, less than; ha, hectare]

| Land cover update | Count | Site only hectares | Footprint disturbed hectares | Road kilometers | Pipeline kilometers | Hectares per site | Disturbed hectares per site | Road kilometers per site |
|---|---|---|---|---|---|---|---|---|
| Impoundments (<0.4 ha) | 67 | 11.9 | | | | 0.2 | | |
| Lycoming County (322,730 hectares) | | | | | | | | |
| All infrastructure | 93 | 211.7 | 421.0 | 37.0 | 73.7 | 2.3 | 4.6 | 0.4 |
| All sites and roads | 93 | 211.7 | | 37.3 | | | | |
| MS sites and roads | 78 | 191.3 | 233.3 | 36.2 | | 2.5 | 3.0 | 0.4 |
| Non-MS sites and roads | 5 | 8.5 | 11.6 | 2.2 | | 1.6 | 2.3 | 0.3 |
| Other infrastructure/ nonpermitted sites and roads | 15 | 20.4 | 31.5 | 8.2 | | 1.6 | 2.1 | 0.5 |
| Dual sites | 5 | 8.5 | | | | | | |
| Pipelines | 19 | 174.9 | 183.0 | | 73.7 | | | |
| Impoundments (>0.4 ha) | 12 | 10.3 | | | | 0.9 | | |
| Impoundments (<0.4 ha) | 40 | 2.8 | | | | 0.1 | | |

Land cover change is the initial impact of disturbance and can have long-term effects on ecological integrity and functions. Table 3 lists the percent land cover by county for 2001 and percent land cover and change for the updated 2010 landscape. The land cover change for the updated landscape is further divided into the values attributable to Marcellus sites; non-Marcellus sites; other infrastructure including nonpermitted sites; and pipelines, each with their associated roads. Given that the natural land cover of Pennsylvania is forest (Kuchler, 1964), the 2001 land cover provides a measure of the impacts prior to most natural gas resource development; the changes between 2004 and 2010 have increased these impacts. Of particular interest are the forest cover and its relation to the critical value 59.28 percent from percolation theory (Gardner and others, 1987; O'Neill and others, 1997). Below this value, the landscape structure rapidly breaks down into isolated patches, thereby changing forest resilience and habitat corridors. The results indicate the following changes based on 2004–2010 natural gas development:

- In both Lycoming and Fayette Counties, the primary land covers were forest (approximately 74 percent for Lycoming County and 68 percent for Fayette County), agriculture (17 percent and 19 percent, respectively), and developed (5 percent and 11 percent, respectively). Natural gas resource development had the greatest impact on forest and agricultural land cover.
- Both counties were above 59.28 percent forest in 2001 and forest has been impacted by recent natural gas resource development. Percent forest declined by 0.45 percent (-1755 ha) in Fayette County and 0.07 percent (-433 ha) in Lycoming County.
- In Fayette County, forest was the class most impacted by natural gas extraction activities. Of these activities non-Marcellus sites had the largest impact decreasing forest area by 0.35 percent (-722 ha).

Agriculture was the second most impacted class by natural gas extraction activities and decreased by 0.36 percent (-536.7 ha).

- In Lycoming County, forest was the most affected by natural gas extraction activities. Of these activities, Marcellus sites had the greatest impact, decreasing forested areas by 0.04 percent, (-129 ha). Agriculture was the second most impacted class by natural gas extraction and decreased 0.05 percent (-96.8 ha).

**Table 3.** Percent land cover (2001) and land cover change (2004–2010) calculated for each county.

[MS, Marcellus Shale site; non-MS, non-Marcellus Shale site]

| Land cover | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fayette County | | | | | | | | | | | |
| Forest | 68.28 | 67.83 | -0.45 | 68.21 | -0.07 | 67.93 | -0.35 | 68.18 | -0.1 | 68.27 | -0.01 |
| Agriculture | 19.09 | 18.73 | -0.36 | 19.01 | -0.08 | 18.83 | -0.26 | 19.04 | -0.05 | 19.09 | 0 |
| Developed | 10.99 | 10.95 | -0.04 | 10.98 | -0.01 | 10.95 | -0.04 | 10.98 | -0.01 | 10.99 | 0 |
| Grassland - herbaceous | 0.04 | 0.04 | 0 | 0.04 | 0 | 0.04 | 0 | 0.04 | 0 | 0.04 | 0 |
| Water | 1.17 | 1.17 | 0 | 1.17 | 0 | 1.17 | 0 | 1.17 | 0 | 1.17 | 0 |
| Barren | 0.42 | 0.42 | 0 | 0.42 | 0 | 0.42 | 0 | 0.42 | 0 | 0.42 | 0 |
| Wetlands | 0.01 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0 |
| Gas extraction disturbance | | 0.85 | 0.85 | 0.16 | 0.16 | 0.65 | 0.65 | 0.16 | 0.16 | 0.1 | 0.01 |
| Lycoming County | | | | | | | | | | | |
| Forest | 74.22 | 74.15 | -0.07 | 74.18 | -0.04 | 74.22 | 0 | 74.22 | 0 | 74.19 | -0.03 |
| Agriculture | 17.66 | 17.61 | -0.05 | 17.63 | -0.03 | 17.66 | 0 | 17.66 | 0 | 17.64 | -0.02 |
| Developed | 5.35 | 5.35 | 0 | 5.35 | 0 | 5.35 | 0 | 5.35 | 0 | 5.35 | 0 |
| Grassland - herbaceous | 0.32 | 0.32 | 0 | 0.32 | 0 | 0.32 | 0 | 0.32 | 0 | 0.32 | 0 |
| Water | 0.70 | 0.70 | 0 | 0.70 | 0 | 0.70 | 0 | 0.70 | 0 | 0.70 | 0 |
| Barren | 0.15 | 0.15 | 0 | 0.15 | 0 | 0.15 | 0 | 0.15 | 0 | 0.15 | 0 |
| Wetlands | 0.41 | 0.41 | 0 | 0.41 | 0 | 0.41 | 0 | 0.41 | 0 | 0.41 | 0 |
| Scrub - shrub | 1.18 | 1.18 | 0 | 1.18 | 0 | 1.18 | 0 | 1.18 | 0 | 1.18 | 0 |
| Gas extraction disturbance | | 0.13 | 0.13 | 0.07 | 0.07 | 0 | 0 | 0.01 | 0.01 | 0.06 | 0.06 |

## Land Cover Metrics of Interest

There are numerous landscape metrics, many of which are redundant. Table 4 lists the total area, number of patches, total edge, mean fractal index, contagion, and evenness metrics for the 2001 county landscape, and the metrics and change for the updated 2010 landscape. The metrics and change for the updated landscape are further divided into the values attributable to Marcellus sites; non-Marcellus sites; other infrastructure including nonpermitted sites; and pipelines, each with their associated roads. These metrics were chosen for their overall indication of human impacts on the landscape and environmental quality (O'Neill and others, 1997). Increase in the edge, especially between unlike land covers, indicates declining resilience of the natural land cover and movement of species, while the decrease in the mean fractal index ($1 \le x \le 2$) indicates an increase in human use. Evenness ($0 \le x \le 1$, where 0 indicates one land cover class and 1 indicates even distribution across land cover classes) indicates the relative heterogeneity of the landscape and is the inverse of the dominance measure (McGarigal and others, 2002) recommended by O'Neill and others (1997). Contagion ($0 < x \le 100$, disaggregated to aggregated) is an indicator that measures the degree of "clumpiness" among the classes of land cover features. The results indicate the following changes occurred based on 2004-2010 natural gas development:

- Total edge increased by 659.2 km and 261.0 km for Fayette and Lycoming Counties, respectively. The largest amount of change is attributable to non-Marcellus sites in Fayette County, whereas in Lycoming County the largest amount of change is attributable to pipeline construction closely followed by Marcellus sites.
- Mean fractal index is low for both counties, which indicates a substantially disturbed landscape for both Fayette and Lycoming Counties. Fayette County is most affected by non-MS sites, while Lycoming County is not dominated by any one single segment of infrastructure.
- Contagion shows a moderate level of clumped land cover for both counties. Lycoming County has a slightly higher level of contagion than Fayette County. The influence of pipelines had the greatest effect and non-MS infrastructure the least effect on contagion in Fayette County, while in Lycoming County contagion effects were similarly influenced by all infrastructure types.
- Evenness has similar values for each infrastructure type. Given that the expected land cover is all forest and an evenness value approaching 0, this calculated evenness value indicates a substantially disturbed landscape.
- Evenness also shows a moderate level of heterogeneity for both counties with no one land cover dominating.

**Table 4.** Landscape metrics by county for 2001 (original land cover) and as updated for natural gas development disturbance (2004–2010).
[Note: Categories are not mutually exclusive; MS, Marcellus Shale site; non-MS, non-Marcellus Shale site; ha, hectare; km, kilometer]

| Metric | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines and roads | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fayette County | | | | | | | | | | | |
| Total area | 206,438 | 206,438 | 0 | 206,438 | 0 | 206,438 | 0 | 206,438 | 0 | 206,438 | 0 |
| Total edge (km) | 14,318.4 | 14,977.6 | 659.2 | 14,378.0 | 59.6 | 14,872.4 | 554.0 | 14,481.7 | 163.4 | 14,323.8 | 5.5 |
| Mean fractal index | 1.1062 | 1.0971 | -0.0091 | 1.105 | -0.0012 | 1.0984 | -0.0078 | 1.1037 | -0.0025 | 1.106 | -0.0002 |
| Contagion | 71.7179 | 72.1595 | 0.4416 | 73.2325 | 1.5146 | 72.4135 | 0.6956 | 73.1861 | 1.4682 | 73.5128 | 1.7949 |
| Evenness | 0.566 | 0.563 | -0.003 | 0.5559 | -0.0101 | 0.5611 | -0.0049 | 0.5562 | -0.0098 | 0.5545 | -0.0115 |
| Lycoming County | | | | | | | | | | | |
| Total area | 322,730 | 322,730 | 0 | 322,730 | 0 | 322,730 | 0 | 322,730 | 0 | 322,730 | 0 |
| Total edge (km) | 16,950.1 | 17,211.1 | 261.0 | 17,060.0 | 109.9 | 16,956.0 | 6.0 | 16,972.8 | 22.7 | 17,118.0 | 167.9 |
| Mean fractal index | 1.1319 | 1.1309 | -0.0010 | 1.1315 | -0.0004 | 1.1318 | -0.0001 | 1.1318 | -0.0001 | 1.1314 | -0.0005 |
| Contagion | 76.9200 | 77.9010 | 0.9810 | 78.0112 | 1.0912 | 78.1475 | 1.2275 | 78.1304 | 1.2104 | 78.0222 | 1.1022 |
| Evenness | 0.4741 | 0.4681 | -0.0060 | 0.4675 | -0.0066 | 0.4667 | -0.0074 | 0.4668 | -0.0073 | 0.4673 | -0.0068 |

## Forest Fragmentation

Disturbance in the landscape will affect forests by fragmentation, which is the process of dividing large land cover (for example, forest) into smaller segments called patches. A patch is defined as adjacent (forest) pixels, including diagonals. A landscape with many small patches is representative of a highly fragmented landscape. Fragmented forests provide habitat for edge species, but are poor for interior species, and are less likely to provide migration corridors.

Fragmentation may be evaluated by change in the number of patches and by change in the mean and (or) median patch size. Table 5 compares the changing forest patch metrics for the 2001 land cover, the updated 2010 land cover, and subsets of the updated 2010 land cover based on Marcellus infrastructure, non-Marcellus infrastructure, other infrastructure, and pipelines. The results indicate the following changes occurred based on 2004–2010 natural gas development:

- Forests became more fragmented due to natural gas resource development. Both Fayette and Lycoming Counties contained more, but smaller forest patches in 2010 than in 2001.
- Fayette County forest patches increased by 981 patches; most (779 patches) were attributable to non-Marcellus sites. These patches initially averaged 55.4 ha, but that average was reduced by almost 16 ha in 2010.
- Lycoming County forest patches increased by 80 patches; most (60 patches) were attributable to pipeline construction. These patches initially averaged about 106 ha and were reduced by 3.7 ha.
- While Fayette County is approximately two-thirds the size of Lycoming, Fayette County saw a 40-percent increase in forest patches, while Lycoming saw only a 3-percent increase in forest patches. This difference indicates a substantially more disturbed landscape in Fayette County, due to the greater presence of non-MS infrastructure.

**Table 5.** Forest fragmentation metrics by county for 2001 (original land cover) and as updated for natural gas development disturbance (2004–2010).

[Note: Categories are not mutually exclusive; MS, Marcellus Shale site; non-MS, non-Marcellus Shale site]

| Distribution statistics | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fayette County | | | | | | | | | | | |
| Number of patches | 2,543 | 3,524 | 981.00 | 2,664 | 121.00 | 3,322 | 779.00 | 2,801 | 258.00 | 2,564 | 21.00 |
| Forest patch area mean | 55.43 | 39.73 | -15.69 | 52.86 | -2.57 | 42.21 | -13.21 | 50.25 | -5.17 | 54.97 | -0.46 |
| Forest patch area median | 0.72 | 0.51 | -0.21 | 0.71 | -0.01 | 0.54 | -0.18 | 0.64 | -0.08 | 0.72 | 0.00 |
| Lycoming County | | | | | | | | | | | |
| Number of patches | 2,257 | 2,337 | 80.00 | 2,274 | 17.00 | 2,259 | 2.00 | 2,263 | 6.00 | 2,317 | 60.00 |
| Forest patch area mean | 106.13 | 102.40 | -3.73 | 105.28 | -0.85 | 106.03 | -0.10 | 105.84 | -0.29 | 103.34 | -2.79 |
| Forest patch area median | 0.73 | 0.72 | -0.01 | 0.72 | -0.01 | 0.73 | 0.00 | 0.73 | 0.00 | 0.72 | -0.01 |

Figure 11 illustrates the spatial distribution of the change in the number of forest patches by watershed. Note the relation between disturbance and the change in the number of forest patches. The increasing number of forest patches in some watersheds indicates an increasingly fragmented landscape with habitat implications for many species.

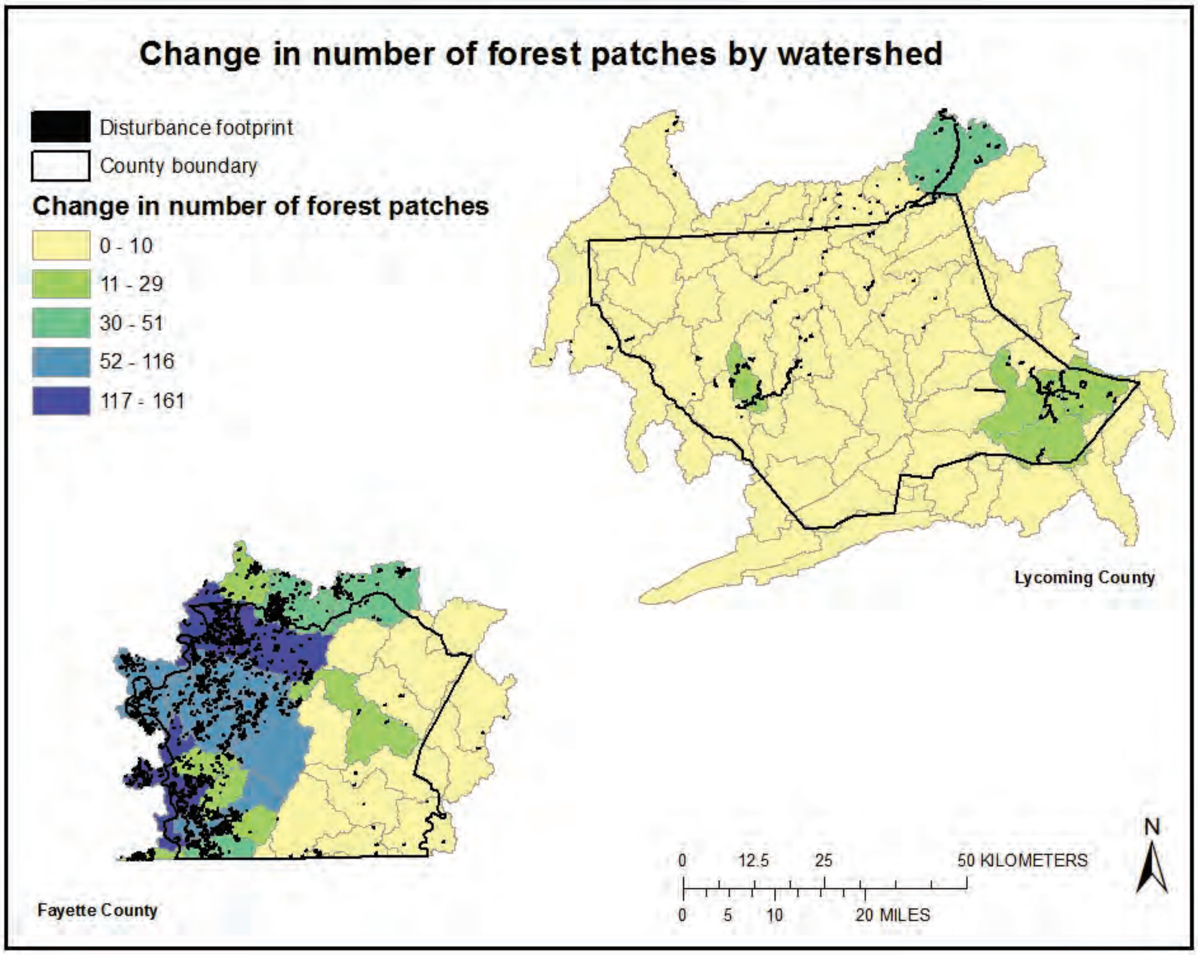

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing the increasing fragmentation in Fayette and Lycoming Counties, Pennsylvania. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (*U.S.* Geological Survey, 2011a)].

## Interior and Edge Forest

Forest condition (interior and edge) is another way to evaluate the state of the forest. In particular, interior forest is subject to more rapid decline than other segments of the forest. Table 6 shows the change in interior forest and edge forest based on natural gas resource development and the types of natural gas extraction infrastructure. Figures 12 and 13, respectively, illustrate the spatial distribution by watershed of change in percent interior forest and the spatial distribution of change in percent edge forest. The results indicate the following changes occurred based on 2004–2010 natural gas development:

- Fayette County lost 0.45 percent forest (-929.0 ha), which constituted a 1.17-percent loss (-2415.3 ha) of interior forest and a gain of 0.5 percent edge forest (1032.2 ha). Non-Marcellus site development was the major contributor of forest loss in Fayette County.
- Lycoming County lost 0.1 percent forest (-225.9 ha), which constituted about a 0.2-percent loss of interior forest (-710.0 ha) and a gain of about 0.1 percent in edge forest (419.6 ha). Marcellus site development and pipeline construction were the major contributors to forest loss in Lycoming County.
- The metrics suggest that the interior forest loss is two to three times that of the overall forest loss, and the gain in edge forest equals the overall loss of forest. Consequences of natural gas extraction are therefore mainly felt in the loss of interior forest.

**Table 6.** Change in percent interior forest and percent edge forest by county for 2001 (original land cover) and as updated for natural gas development disturbance (2004–2010).

[Note: Categories are not mutually exclusive; MS, Marcellus Shale site; non-MS, non-Marcellus Shale site]

| Distribution statistics | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fayette County | | | | | | | | | | | |
| Percent forest | 69.08 | 68.63 | -0.45 | 69.02 | -0.06 | 68.74 | -0.35 | 68.99 | -0.09 | 69.08 | 0.00 |
| Percent interior forest | 48.36 | 47.19 | -1.17 | 48.25 | -0.12 | 47.40 | -0.96 | 48.09 | -0.27 | 48.36 | 0.00 |
| Percent forest edge | 15.57 | 16.07 | 0.50 | 15.60 | 0.03 | 15.99 | 0.42 | 15.70 | 0.13 | 15.57 | 0.00 |
| Lycoming County | | | | | | | | | | | |
| Percent forest | 74.74 | 74.67 | -0.07 | 74.7 | -0.04 | 74.74 | 0 | 74.74 | 0 | 74.71 | -0.03 |
| Percent interior forest | 63.27 | 63.05 | -0.22 | 63.15 | -0.12 | 63.27 | 0 | 63.25 | -0.02 | 63.16 | -0.11 |
| Percent forest edge | 8.63 | 8.76 | 0.13 | 8.7 | 0.07 | 8.63 | 0 | 8.65 | 0.02 | 8.7 | 0.07 |

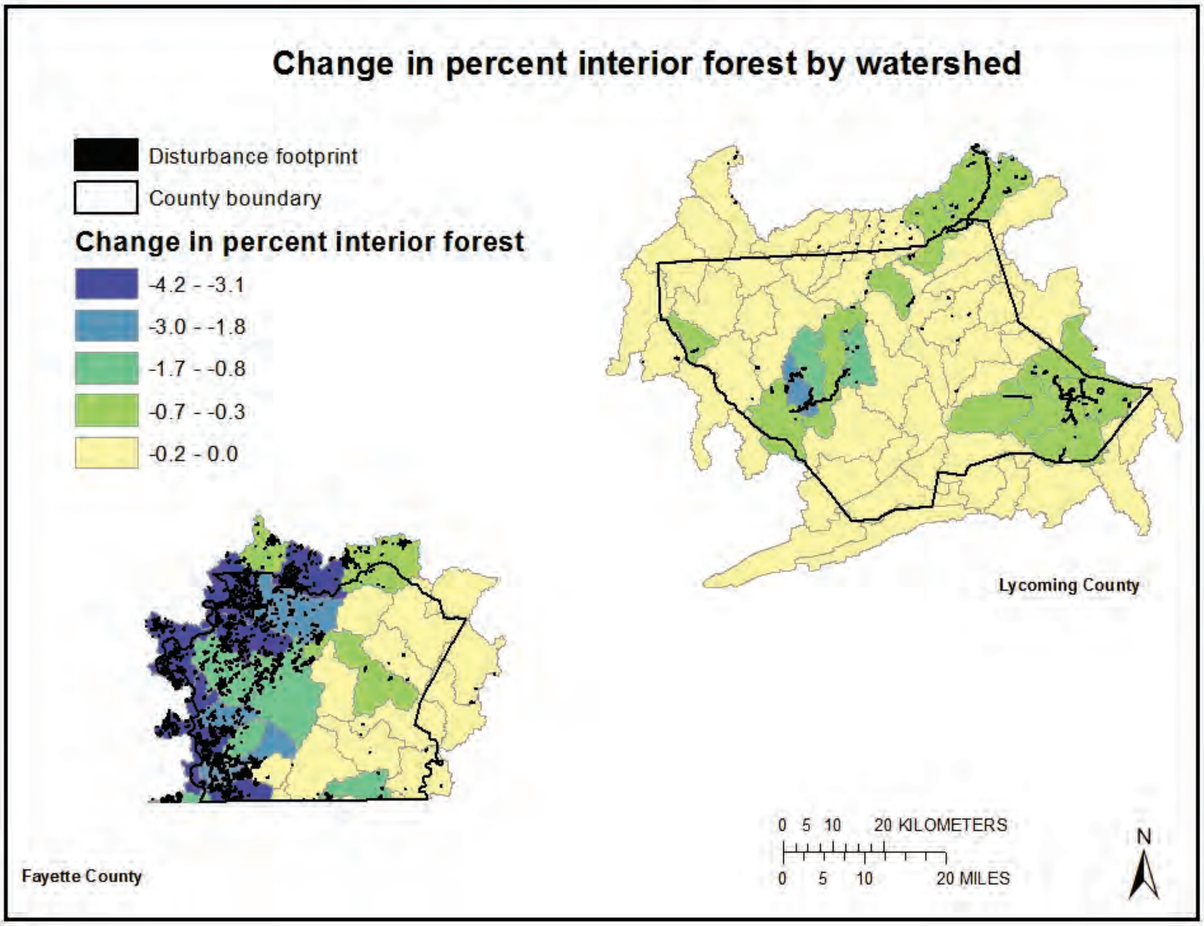

**Figure 12.** Change in percent interior forest by watershed in Fayette and Lycoming Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

## Conclusion

Overall, the results indicate that Fayette County is more heavily disturbed than Lycoming County. This difference is largely due to the greater presence of non-Marcellus activity and the smaller size of Fayette County compared to Lycoming County. These results are indicative of how natural gas extraction in Pennsylvania is affecting the landscape configuration with agricultural and forested areas being converted to natural gas extraction. The disturbance and effects of both Marcellus and non-Marcellus development are clearly different between the counties; Fayette County has higher activity (Marcellus and non-Marcellus) than Lycoming County. The effects of non-Marcellus sites are greater in Fayette County than in Lycoming County, where Marcellus site activities predominate over non-Marcellus sites, but it is important to note that the combined effect of both activities is substantial.

The fractal dimension, contagion, and dominance landscape metrics were reported based on recommendations of O'Neill and others (1997); however, these metrics do not appear to be important in these counties. They may be of greater importance for other counties and are reported here for consistency.

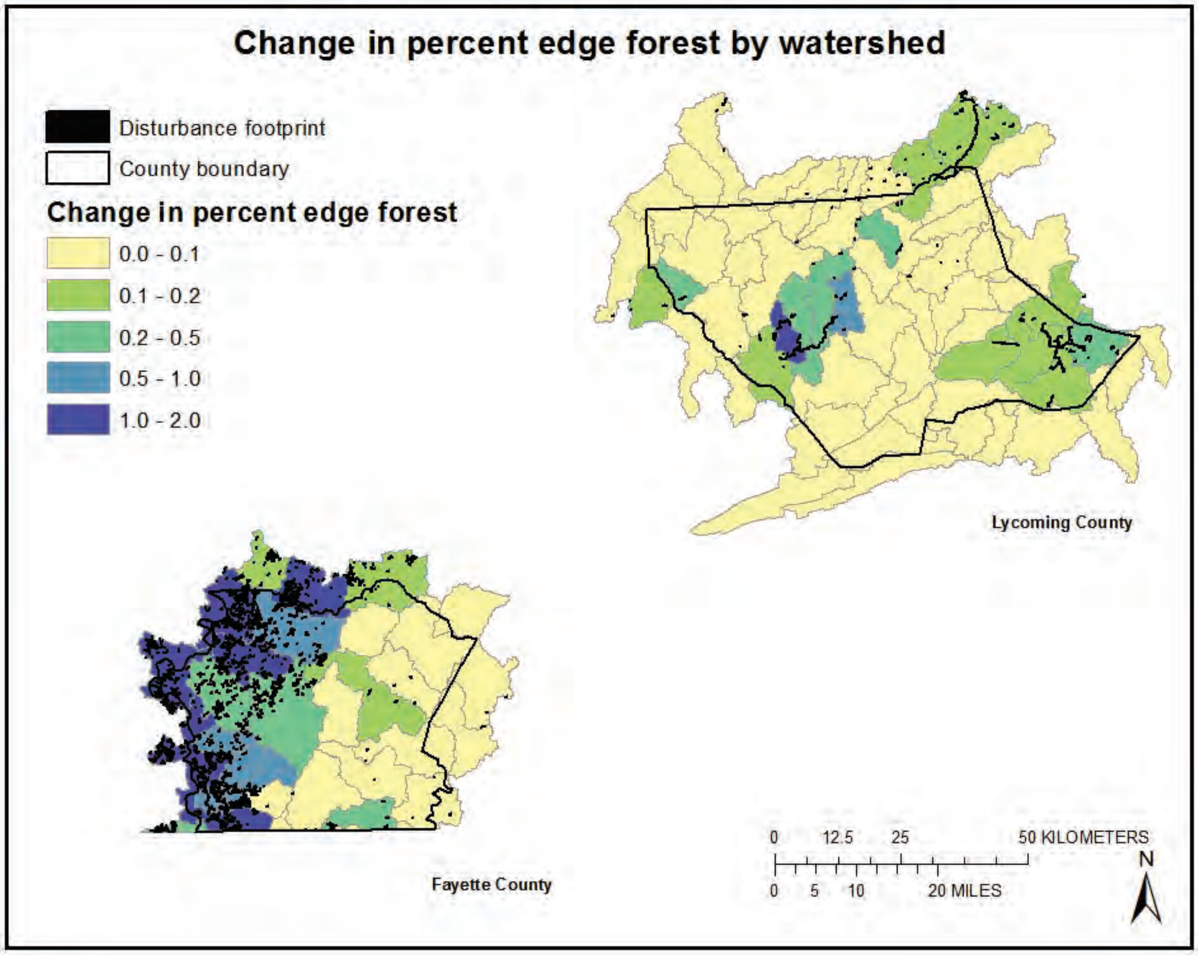

**Figure 13.** Change in percent of edge forest by watershed in Fayette and Lycoming Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

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# Landscape Consequences of Natural Gas Extraction in Greene and Tioga Counties, Pennsylvania, 2004–2010

By E.T. Slonecker, L.E. Milheim, C.M. Roig-Silva, and G.B. Fisher

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Suggested citation:
Slonecker, E.T., Milheim, L.E., Roig-Silva, C.M., and Fisher, G.B., 2012, Landscape consequences of natural gas extraction in Greene and Tioga Counties, Pennsylvania, 2004–2010: U.S. Geological Survey Open File Report 2012–1220, 32 p.

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# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Area | |
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

# Landscape Consequences of Natural Gas Extraction in Greene and Tioga Counties, Pennsylvania, 2004–2010

By E.T. Slonecker, L.E. Milheim, C.M. Roig-Silva, and G.B. Fisher

## Abstract

Increased demands for cleaner burning energy, coupled with the relatively recent technological advances in accessing unconventional hydrocarbon-rich geologic formations, have led to an intense effort to find and extract natural gas from various underground sources around the country. One of these sources, the Marcellus Shale, located in the Allegheny Plateau, is currently undergoing extensive drilling and production. The technology used to extract gas in the Marcellus shale is known as hydraulic fracturing and has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on water resources. Nonetheless, development of natural gas extraction wells in the Marcellus Shale is only part of the overall natural gas story in the area of Pennsylvania. Coalbed methane, which is sometimes extracted using the same technique, is commonly located in the same general area as the Marcellus Shale and is frequently developed in clusters across the landscape. The combined effects of these two natural gas extraction methods create potentially serious patterns of disturbance on the landscape. This document quantifies the landscape changes and consequences of natural gas extraction for Greene County and Tioga County in Pennsylvania between 2004 and 2010. Patterns of landscape disturbance related to natural gas extraction activities were collected and digitized using National Agriculture Imagery Program (NAIP) imagery for 2004, 2005/2006, 2008, and 2010. The disturbance patterns were then used to measure changes in land cover and land use using the National Land Cover Database (NLCD) of 2001. A series of landscape metrics are also used to quantify these changes and are included in this publication.

## Introduction: Natural Gas Extraction

The need for cleaner burning energy, coupled with the relatively recent technological advances in accessing hydrocarbon-rich geologic formations, has led to an intense effort to find and extract natural gas from various underground sources around the country. One of these formations, the Marcellus Shale, is currently the target of extensive drilling and production in the Allegheny Plateau. Marcellus Shale generally extends from New York to West Virginia as shown in figure 1 (Coleman and others, 2011). Coleman and others (2011) defined assessment units (AU) of Marcellus Shale production based on the geology of the region.

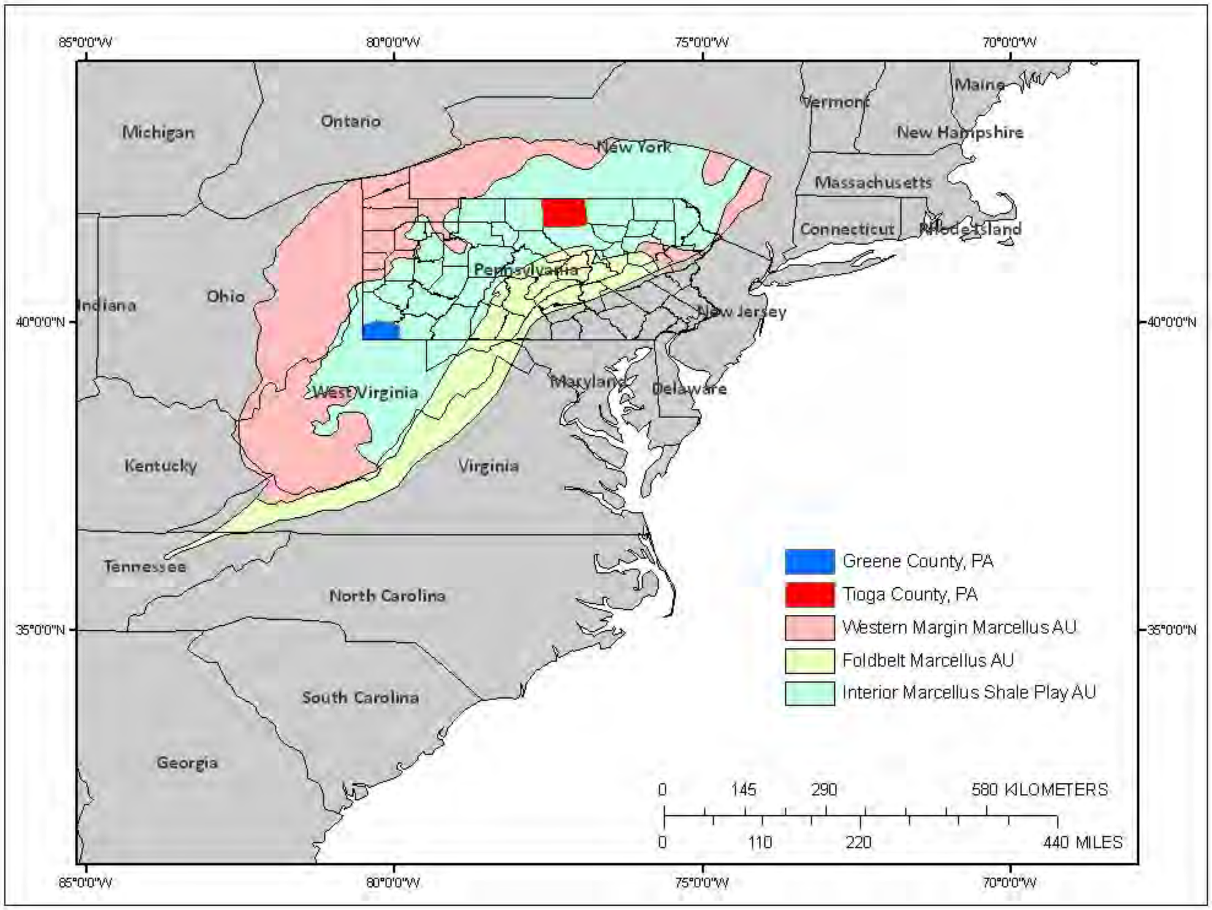

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus Shale AU is expected to be a major production area for natural gas (Coleman and others, 2011). Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

The overall landscape effects of natural gas development have been considerable. Over 9,600 Marcellus Shale gas drilling permits and over 49,500 non-Marcellus Shale permits have been issued from 2000 to 2011 in Pennsylvania (Pennsylvania Department of Environmental Protection, 2011) and over 2,300 Marcellus Shale permits in West Virginia (West Virginia Geological and Economic Survey, 2011), with most of the development activity occurring since 2005.

The Marcellus Shale is generally located 600 to 3,000 meters below the land surface (Coleman and others, 2011). Gas and petroleum liquids are produced with a combination of vertical and horizontal drilling techniques, coupled with a process of hydraulically fracturing the shale formation, known as "fracking," which releases the natural gas.

The hydraulic-fracturing process has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on groundwater and drinking-water resources.

However, with all of the development of natural gas wells in the Marcellus Shale it is only part of the overall natural gas story in this area. Coalbed methane, which is extracted in similar ways, is commonly located in the same general area as the Marcellus Shale. The coalbed methane wells are much shallower and less productive but are often located in clusters that dot large areas of the landscape, with nearly 60,000 total gas wells. There may be both types of wells in a given area. With the accompanying areas of disturbance, well pads, new roads, and pipelines from both types of natural gas wells, the effect on the landscape is often dramatic. Figure 2 shows examples of a pattern of landscape change from forest to forest interspersed with gas extraction infrastructure. These landscape effects have consequences for the ecosystems, wildlife, and human populations that are collocated with natural gas extraction activities. This document examines the landscape consequences of gas extraction for two areas of current Marcellus Shale and non-Marcellus Shale natural gas extraction activity.

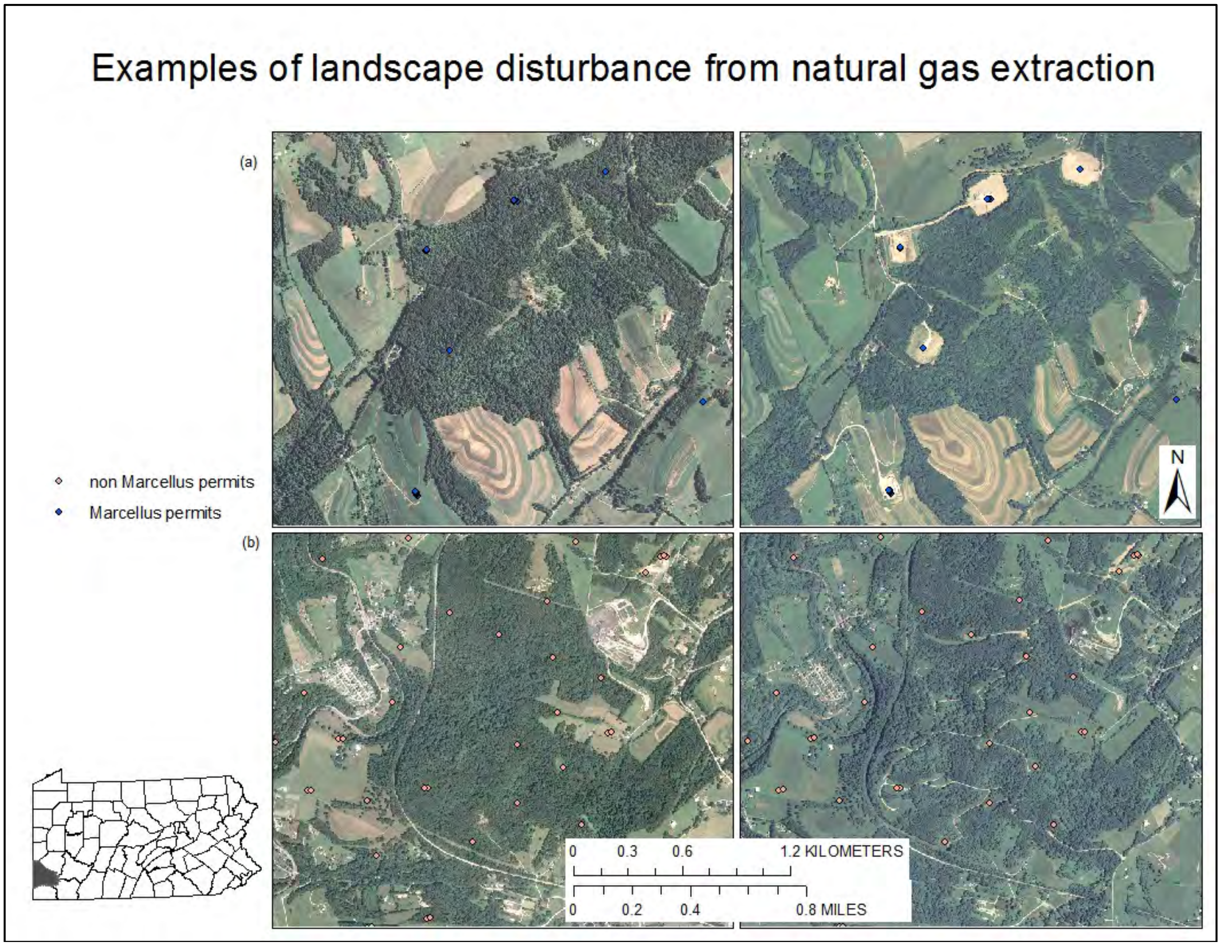

**Figure 2.** Examples forested landscapes in Washington County, Pennsylvania, showing the spatial effects of roads, well pads, and pipelines related to (a) Marcellus Shale and (b) conventional natural gas development. Inset shows the location of the image. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer)* (U.S. Geological Survey, 2011)].

## Location

This assessment of landscape effects focuses on two counties involved in the Marcellus Shale area of development known as the “Play”—Greene County and Tioga County in Pennsylvania. These counties were chosen for their position within the "sweet spots" of exceptionally productive Marcellus Shale (Stevens and Kuuskraa, 2009). Figure 3 below identifies the selected counties in relation to the Marcellus Shale Play and the distribution of Marcellus and non-Marcellus gas extraction permits granted by Pennsylvania.

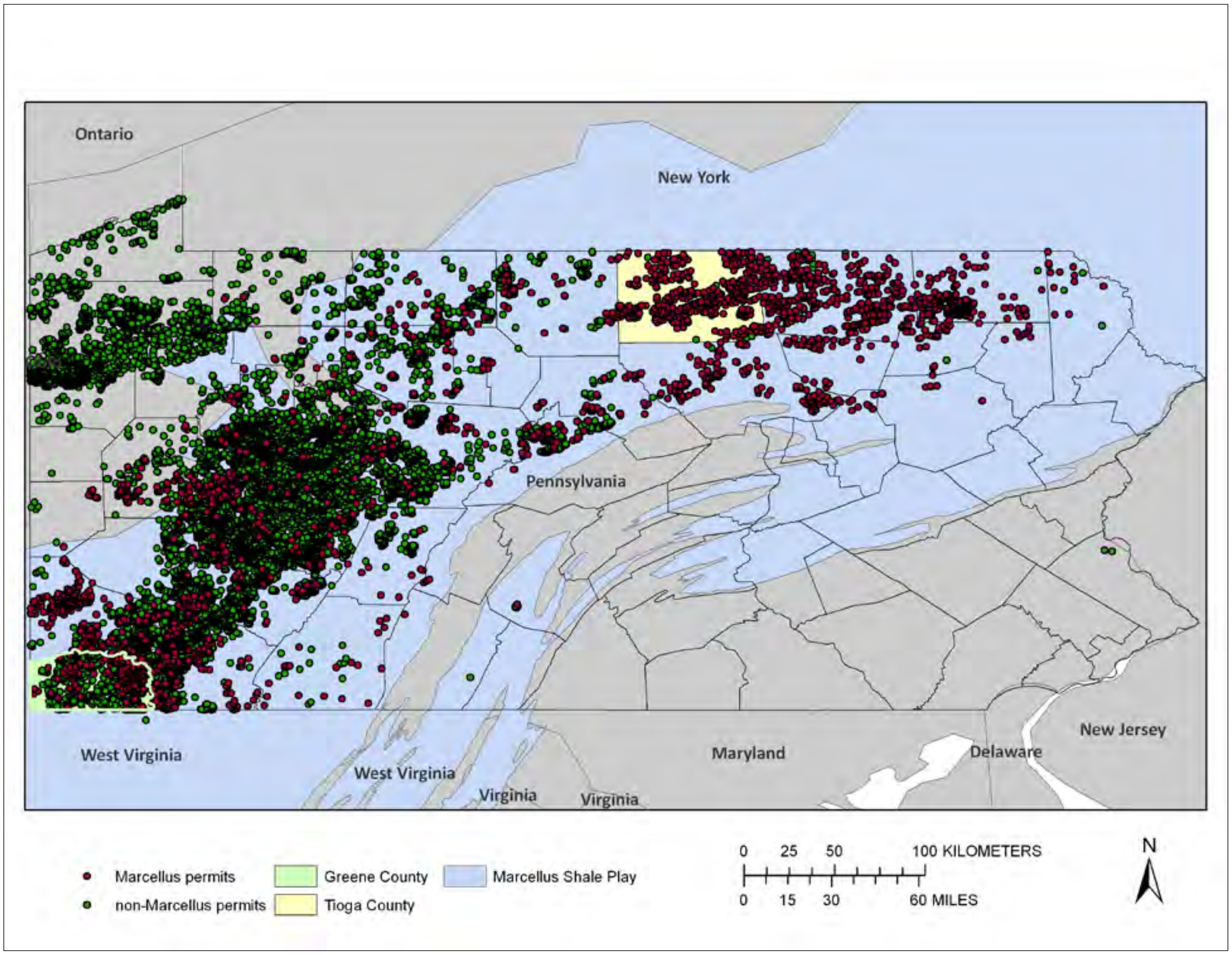

**Figure 3**. The distribution of Marcellus and non-Marcellus natural gas permits issued between 2004 and 2010 within Pennsylvania, the focal counties of Greene and Tioga, and their relation to the Marcellus Shale Play Interior assessment unit. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## The Biogeography of Pennsylvania Forests

Forests are a critical land cover in Pennsylvania. Prior to the European settlements, Pennsylvania was almost completely forested and even today, with modern agriculture, urban growth and population growth, Pennsylvania is still roughly 60 percent forest. Pennsylvania forests of the 17th century were diverse but were dominated by beech and hemlock, which composed 65 percent of the total forest (Pennsylvania Department of Conservation and Natural Resources, 2011). However, in the late 19th century, Pennsylvania became the country's leading source of lumber, in which a number of products, from lumber to the production of tannic acid, were generated from the forestry industry (Pennsylvania Department of Conservation and Natural Resources, 2011). By the early 20th century, most of Pennsylvania's forests had been harvested. Soon after most of the trees were felled, wildfires, erosion, and flooding became prevalent, especially in the Allegheny Plateau region (Pennsylvania Parks and Forests Foundation, 2010).

The 20th century saw a resurgence in Pennsylvania forests. The Weeks Act of 1911 authorized the Federal purchase of forest land on the headwaters of navigable rivers to control the flow of water downstream and act as a measure of flood control for the thriving steel industry of Pittsburgh. Slowly, the forests began to grow back but with a vastly different composition composed of black cherry, red maple, and sugar maple species (Pennsylvania Parks and Forests Foundation, 2010). For the most part, except for a very few isolated areas in north central Pennsylvania and some State parks, the majority of forest cover is currently of the new composition and not of pre-European forest. Figure 4 shows that today the concentrations of forests in Pennsylvania are highest in the central and north-central parts of the State, which is also the main area of hydraulic-fracturing activity in the Marcellus Shale.

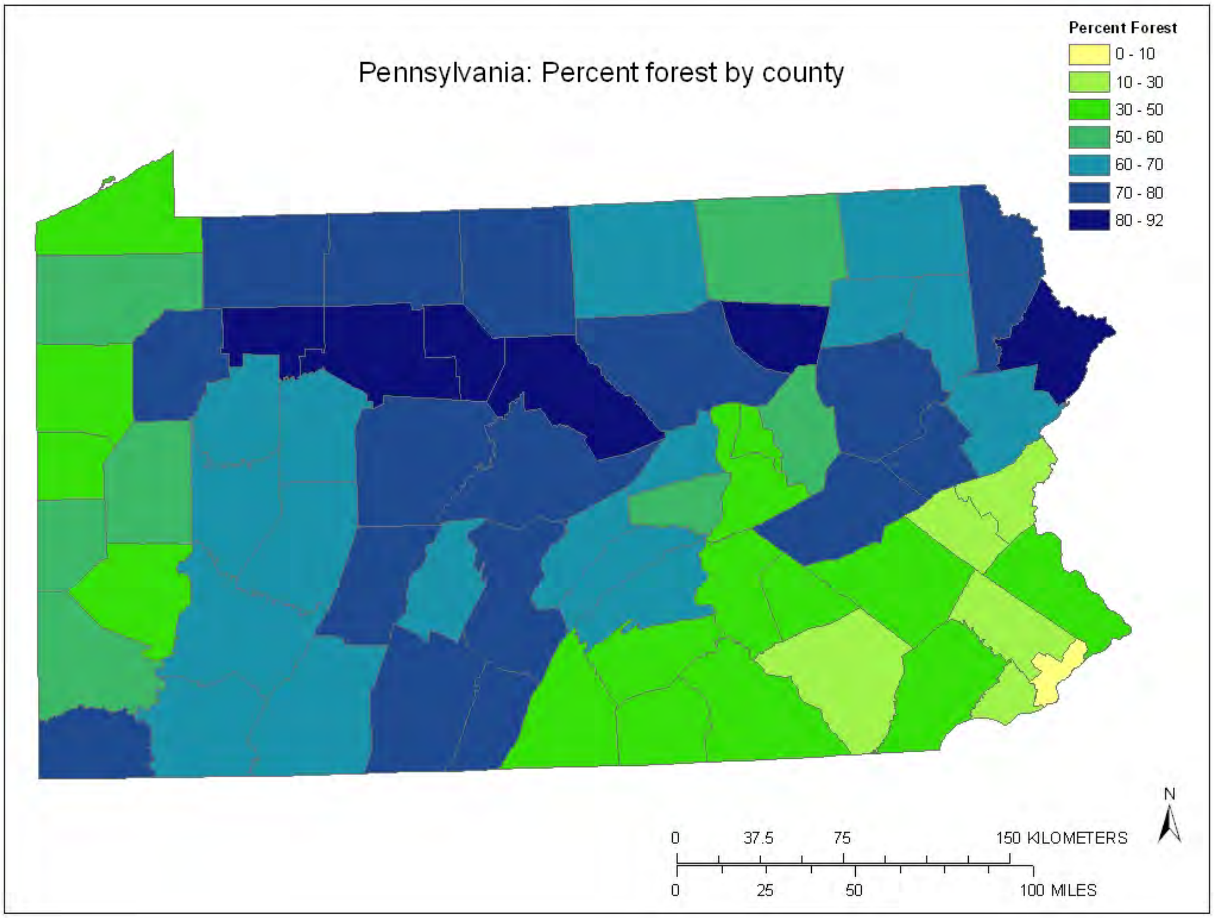

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Data. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

Pennsylvania forests provide critical habitat to a number of plant species such as the sugar maple, the Eastern red cedar, and evergreens that produce berries in the winter. There were a number of animal species that have been eradicated from the region such as elk, moose, North American cougar, bison, and grey wolf (Nilsson, 2005). Today, animal species range from the typical skunk to flying squirrels, and multiple varieties of snakes and bats. However, a diverse population of birds depends on the forests for survival. In the State of Pennsylvania, there are 394 different bird species that are native, including endangered species such as the peregrine falcon and the bald eagle (Gross, 2005).

### Key Research Questions

One key aspect of this research is to quantify the level of disturbance in terms of land use and land cover change by specific disturbance category (well pads, roads, pipelines, and so forth). This quantification will be accomplished by extracting the signatures of disturbance from high-resolution aerial images and then computing landscape metrics in a geographic information systems (GIS) environment.

This research and monitoring effort will attempt to answer the following key research questions:

- What is the level of overall disturbance attributed to gas exploration and development activities and how has this changed over time?
- What are the structural components (land cover classes) of this change and how much change can be attributed to each class?
- How has the disturbance associated with natural gas exploration and development affected the structure, pattern, and process of key ecosystems, especially forests, within the Marcellus Shale Play?
- How will the disturbance stressors affect ecosystem structure and function at a landscape and watershed scale?

## Landscape Metrics and a Landscape Perspective

An important and sometimes overlooked aspect of contemporary gas exploration activity is the geographic profile and spatial arrangement of these activities on the land surface. The function of ecosystems and the services they provide are due in large part to their spatial arrangement on the landscape. Energy exploration and development represents a specific form of land use and land cover change (LULCC) activity that substantially alters certain critical aspects of the spatial pattern, form, and function of landscape interactions.

Changes in land use and land cover affect the ability of ecosystems to provide essential ecological goods and services, which, in turn, affect the economic, public health, and social benefits these ecosystems provide. One of the scientific challenges for geographic science is to understand and calibrate the effects of land use and land cover change and the complex interaction between human and biotic systems at a variety of natural, geographic, and political scales (Slonecker, 2010).

Land use and land cover change, such as the disturbance and the landscape effects of energy exploration, is currently occurring at a relatively rapid pace prompting immediate scientific focus and attention. Understanding the dynamics of land surface change requires an increased understanding of the complex nature of human-environmental systems and requires a suite of scientific tools that include traditional geographic data and analysis methods, such as remote sensing and GIS, as well as innovative approaches to understanding the dynamics of complex natural systems (O’Neill and others, 1997; Turner, 2005; Wickham and others, 2007). One such approach that has gained much recent scientific attention is the landscape indicator, or landscape assessment, approach, which has been developed with the science of landscape ecology (O’Neill and others, 1997).

Landscape assessment utilizes spatially explicit imagery and GIS data on land cover, elevation, roads, hydrology, vegetation, and in situ sampling results to compute a suite of numerical indicators known as **landscape metrics** to assess ecosystem condition. Landscape analysis is focused on the relation between pattern and process and broad-scale ecological relationships such as habitat, conservation, and sustainability. Landscape analysis necessarily considers both biological and socioeconomic issues and relationships. This research explores these relationships and their potential effect on various ecosystems and biological endpoints.

The landscape analysis presented here is based largely on the framework outlined in O'Neill and others (1997). There are many landscape metrics that can be computed and utilized for some analytical purpose. However, it has been shown by several researchers (Wickham and Riitters, 1995; Riitters and others, 1995; Wickham and others, 1997) that many of these metrics are highly correlated, sensitive to misclassification and pixel size, and, to some extent, questionable in terms of additional information value. The key landscape concepts and metrics reported here are discussed below. The actual formulae used to compute these specific metrics can be found in software documentation for FRAGSTATS and ATtILA (McGarigal and others, 2002; Ebert and Wade, 2004).

The concept of landscape metrics, sometimes called landscape indices, is derived from the field of landscape ecology and is rooted in the realization that pattern and structure are important components of ecological process. Landscape metrics are spatial/mathematical indices that have been developed that allow the objective description of different aspects of landscape structures and patterns (McGarigal and others, 2002). They characterize the landscape structure and various processes at both landscape and ecosystem level. Metrics such as average patch size, fragmentation, and interior forest dimension capture spatial characteristics of habitat quality and potential change effects on critical animal and vegetation populations.

Two different geostatistical landscape analysis programs were used to measure the landscape metrics presented in this report. FRAGSTATS (University of Massachusetts, Amherst, Mass.) is a spatial pattern analysis program for quantifying numerous landscape metrics and their distribution, and is available at: *http://www.umass.edu/landeco/research/fragstats/fragstats.html* (McGarigal and others, 2002). ATtILA (Analytical Tools Interface for Landscape Assessments) (U.S. Environmental Protection Agency, Las Vegas, Nev.) is an Arcview 3.x extension [Environmental System Research Institute (Esri), Redlands, Calif.] developed by the U.S. Environmental Protection Agency (USEPA) that computes a number of landscape, riparian, and watershed metrics, and is available at: *http://www.epa.gov/esd/land-sci/attila/* (Ebert and Wade, 2004). Metrics are presented here at the county level and mapped at the watershed level (12-digit Hydrologic Unit Codes).

## Disturbance

Disturbance is a key concept in a landscape analysis approach and in ecology in general. Gas development activities create a number of disturbances across the landscape. In landscape analysis, disturbances are discrete events in space and time that disrupt ecosystem structure and function and change resource availability and the physical environment (White and Pickett, 1985; Turner and others, 2001). When natural or anthropogenic disturbance occurs in natural systems, it generally alters abiotic and biotic conditions that favor the success of different species. Natural gas exploration and development result in spatially explicit patterns of landscape disturbance involving the construction of well pads and impoundments, roads, pipelines, and disposal activities that have structural impacts on the landscape (fig. 2).

Development of multiple sources of natural gas will result in increased traffic from construction, drilling operations (horizontal and vertical), hydraulic fracturing, extraction, transportation, and maintenance activities. The mere presence of humans, construction machinery, infrastructure (for example, well pads and pipelines), roads, and vehicles alone may substantially impact flora and fauna. Increased traffic, especially rapid increases on roads that have historically received little activity, can have detrimental impacts to populations (Gibbs and Shriver, 2005). Forest loss as a result of disturbance, fragmentation, and edge effects has been shown to negatively affect water quality and runoff (Wickham and others, 2008), alter biosphere-atmosphere dynamics that could contribute to climate change (Bonan, 2008; Hayden, 1998), and affect the long-term survival of the forest itself (Gascon and others, 2007). The initial step of landscape analysis is to determine the spatial distribution of disturbance to identify relative hotspots of activity. Disturbance in this report is presented as both graphic files and tables of summary statistics. This knowledge allows greater focus to be placed on specific locations. Figure 5 provides an example of the distribution of natural gas extraction in Bradford County, Pennsylvania. The example also shows how that disturbance is placed with respect to the local land cover.

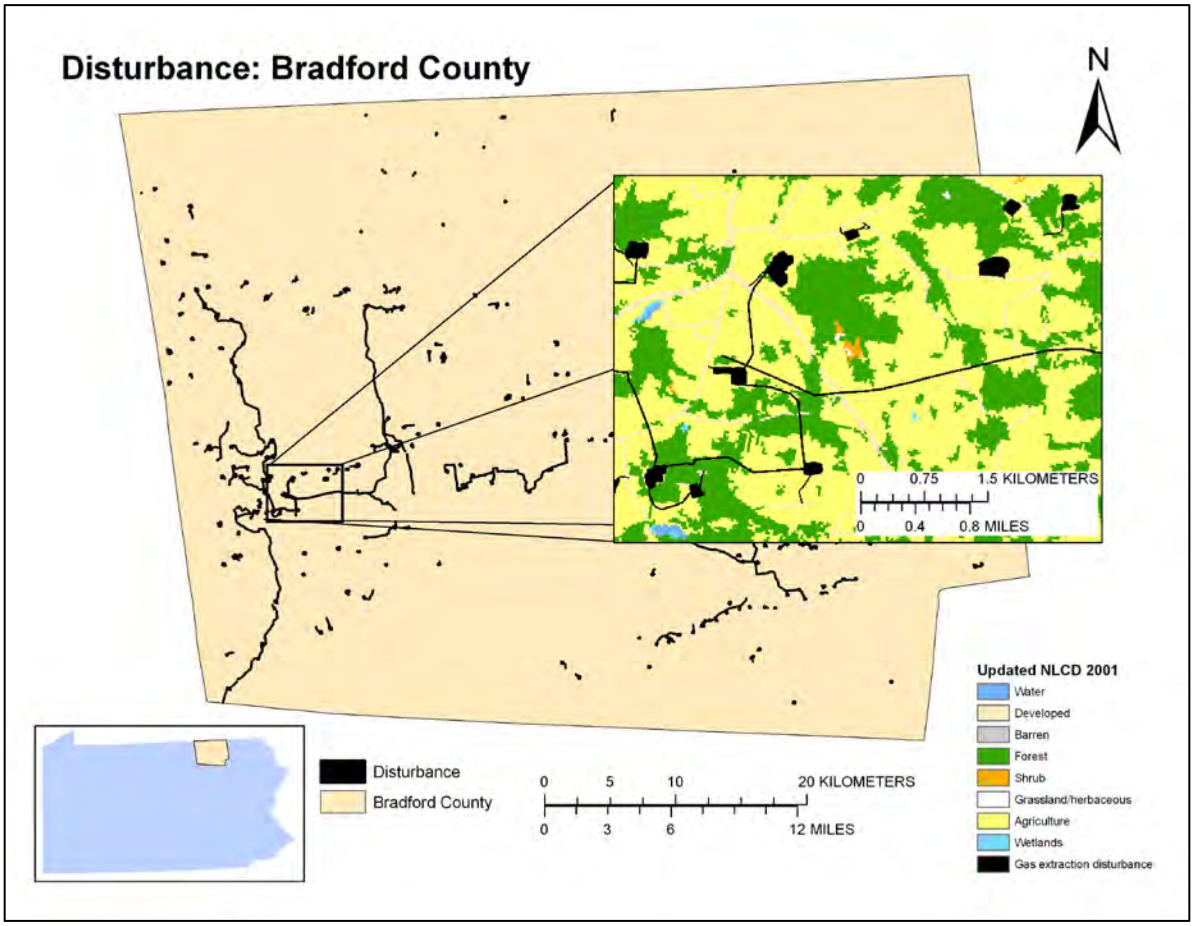

**Figure 5.** Example of the natural gas disturbance footprint of Bradford County, Pennsylvania, embedded within the National Land Cover Dataset (NLCD) 2001. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## Forest Fragmentation

Fragmentation of forest and habitat is a primary concern resulting from current gas development. Habitat fragmentation occurs when large areas of natural landscapes are intersected and subdivided by other, usually anthropogenic, land uses leaving smaller patches to serve as habitat for various species. As human activities increase, natural habitats, such as forests, are divided into smaller and smaller patches that have a decreased ability to support viable populations of individual species. Habitat loss and forest fragmentation can be substantial threats to biodiversity, although research on this topic has not been conclusive (With and Pavuk, 2011).

Gas exploration and development activity can be extreme in their effect on the landscape. The development of numerous secondary roads and pipeline networks crisscrosses and subdivides habitat structure.

Landscape disturbance associated with shale-gas development infrastructure directly alters habitat through loss, fragmentation, and edge effects, which in turn alters the flora and fauna dependent on that habitat. The fragmentation of habitat is expected to amplify the problem of total habitat area reduction for wildlife species, as well as contribute towards habitat degradation. Fragmentation alters the landscape by creating a mosaic of spatially distinct habitats from originally contiguous habitat, resulting in smaller patch size, greater number of patches, and decreased interior to edge ratio (Lehmkuhl and Ruggiero, 1991; Dale and others, 2000). Fragmented habitats generally result in detrimental impacts to flora and fauna, resulting from increased mortality of individuals moving between patches, lower recolonization rates, and reduced local population sizes (Fahrig and Merriam, 1994). The remaining patches may be too small, isolated, and possibly too influenced by edge effects to maintain viable populations of some species. The rate of landscape change can be more important than the amount or type of change because the temporal dimension of change can affect the probability of recolonization for endemic species, which are typically restricted by their dispersal range and the kinds of landscapes in which they can move (Fahrig and Merriam,1994).

While general assumptions and hypotheses can be derived from existing scientific literature involving similar stressors, the specific impacts of habitat loss and fragmentation in the Marcellus Shale Play will depend on the needs and attributes of specific species and communities. A recent analysis of Marcellus well permit locations in Pennsylvania found that well pads and associated infrastructure (roads, water impoundments, and pipelines) required nearly 3.6 hectares (9 acres) per well pad with an additional 8.5 hectares (21 acres) of indirect edge effects (Johnson, 2010). This type of extensive and long-term habitat conversion has a greater impact on natural ecosystems than activities such as logging or agriculture, given the great dissimilarity between gas-well pad infrastructure and adjacent natural areas and the low probability that the disturbed land will revert back to a natural state in the near future (high persistence) (Marzluff and Ewing, 2001). Figure 6 shows an example of the concept of the landscape metric of forest fragmentation.

## Interior Forest

Interior forest is a special form of habitat that is preferred by many plant and animal species and is defined as the area of forest at least 100 meters from the forest edge (Harper and others, 2005). Interior forest is an important landscape characteristic because the environmental conditions, such as light, wind, humidity, and exposure to predators, within the interior forest are different from areas closer to the forest edge. Interior forest habitat is related to the size and distribution of forest patches and is closely tied to the concept of forest or habitat **fragmentation**—the alteration of habitat into smaller, less functional areas. The amount of interior forest can be dramatically affected by linear land use patterns, such as roads and pipelines, which tend to fragment land patches into several smaller patches and destroy available habitat for certain species. Figure 6 shows the general concept of increased fragmentation and reduced interior forest.

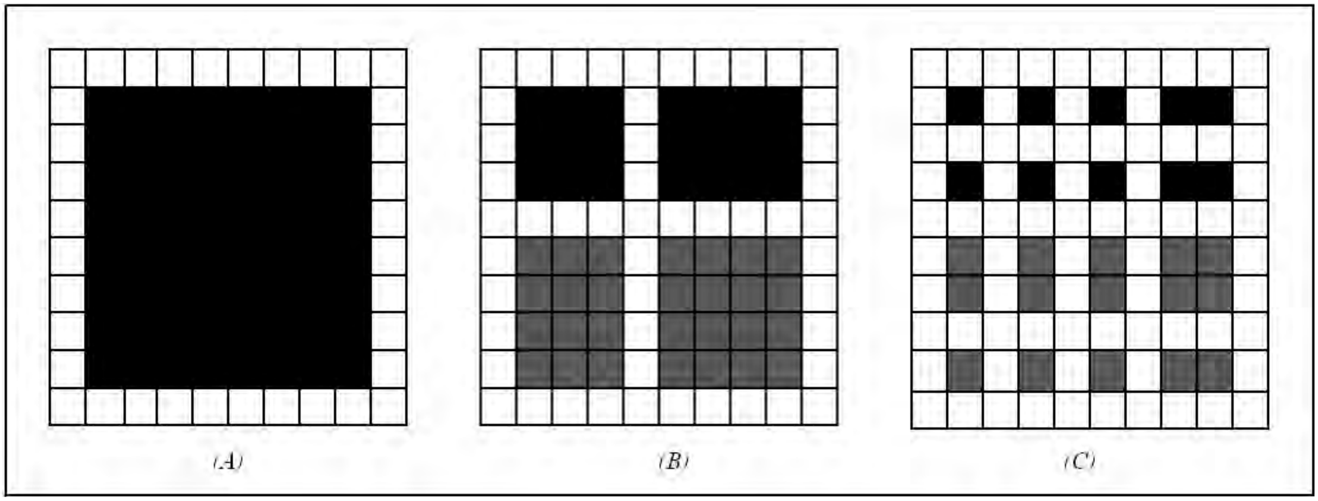

**Figure 6.** Conceptual illustration of interior forest and how critical habitat is affected by linear disturbance. (*A*) High interior area, (*B*) Moderate interior area, and (*C*) Low interior area (Riitters and others, 1996).

## Forest Edge

Forest edge is simply a linear measure of the amount of edges between forest and other land uses in a given area, and especially between natural and human-dominated landscapes. The influence of the two bordering communities on each other is known as the edge effect. When edges are expanded into natural ecosystems, and the area outside the boundary is a disturbed or unnatural system, the natural ecosystem can be affected for some distance in from the edge (Skole and Tucker, 1993). Edge effects are variable in space and time. The intensity of edge effects diminishes as one moves deeper inside a forest, but edge phenomena can vary greatly within the same habitat fragment or landscape (Laurance and others, 2007). Factors that might promote edge-effect variability include the age of habitat edges, edge aspect, and the combined effects of multiple nearby edges, fragment size, seasonality, and extreme weather events.

Spatial variability of edge effects may result from local factors such as the proximity and number of nearby forest edges. Plots with two or more neighboring edges, such as smaller fragment plots, have greater tree mortality and biomass loss. Edge age also influences edge effects. Over time, forest edge is partially sealed by proliferating vines and second growth underbrush growth, which will influence the ability of smaller tree seedlings to survive in this environment. Likewise, the matrix of adjoining vegetation plots will have a strong influence on edge effects. Forest edges adjoined by young regrowth forest provide a physical buffer from wind and light. Extreme weather events also affect the temporal variability in edge effects. Abrupt, artificial boundaries of forest fragments are vulnerable to windstorms, snow and ice, and convectional thunderstorms that can weaken and destroy exposed forest edges. Periodic droughts can also have a more pronounced effect on forest edges that are exposed to drier wind conditions and higher rates of evaporation than interior forest.

## Contagion

Contagion is an indicator that measures the degree of "clumpiness" among the classes of land cover features and is related to patch size and distribution. Contagion expresses the degree to which adjacent pixel pairs can be found in the landscape. Figure 7 shows the general concept of contagion and gives examples of low, medium, and high contagion. Contagion is valuable because it relates an important measure of how landscapes are fragmented by patches. Landscapes of large, less-fragmented patches have a high contagion value and landscapes of numerous small patches have a low contagion value (McGarigal and others, 2002).

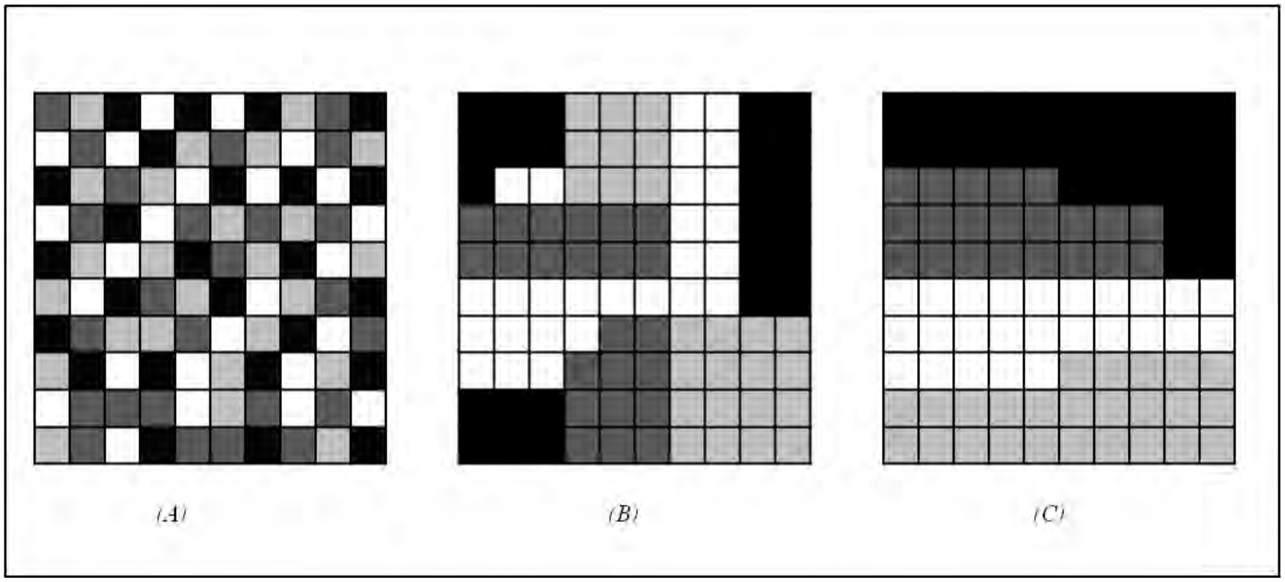

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or "clumped" to one another. *(A)* Low contagion, *(B)* Moderate contagion, and *(C)* High contagion (after Riitters and others, 1996).

## Fractal Dimension

Fractal dimension describes the complexity of patches or edges within a landscape and is generally related to the level of anthropogenic influence in a landscape. Fractal dimension generally measures the relationship of a patch by a perimeter-to-area proportion. Human land uses tend to have simple, circular, or rectangular shapes, of low complexity and, therefore, low fractal dimensions. Natural land covers have irregular edges, complex arrangements and, therefore, higher fractal dimensions. The fractal dimension index ranges between 1 and 2, with 1 indicating high human influences in the landscape and 2 with natural patterns and low human influence (McGarigal and others, 2002).

## Dominance

Dominance is a measure of the relative abundance of different patch types, typically emphasizing either relative evenness or equity in the distribution. Dominance is high when one land cover type occupies a relatively large area of a given landscape, and is low when land cover types are evenly distributed. Dominance is the complement to evenness, which is sometimes used as a similar measure of the relative area of one land cover type over others in the landscape.

Although there are many metrics associated with dominance, here we report on a simple landscape metric—the Simpson's Evenness Index, which is a measure of the proportion of the landscape occupied by a patch type divided by the total number of patch types in the landscape (McGarigal and others, 2002).

## Methodology: Mapping and Measuring Disturbance Effects

High-resolution aerial imagery for each of four timeframes—2004, 2005/2006, 2008, and 2010—were brought into a GIS database, along with additional geospatial data on Marcellus and non-Marcellus well permits and locations, administrative boundaries, ecoregions, and geospatial information on the footprint of the Marcellus Shale Play in Pennsylvania. The imagery was examined for distinct signs of disturbance related to oil and gas drilling and development. The observable features were manually digitized as line and polygon features in a GIS format. The polygons and line features were processed and aggregated into a raster mask used to update existing land cover data. Summary statistics for each county were developed and reported. Detailed landscape metrics were calculated and mapped over watersheds [Hydrological Unit Code (HUC)-12 hydrounits] within and intersecting the boundary of each county.

### Data

#### Sources

High-resolution aerial imagery from the National Agricultural Imagery Program (NAIP) was downloaded for each timeframe. NAIP imagery is flown to analyze the status of agricultural lands approximately every 2 to 3 years (U.S. Department of Agriculture, Farm Service Agency, 2011). The NAIP imagery consists of readily available, high-resolution data that are suitable for detailed analysis of the landscape. NAIP imagery is available from the U.S. Department of Agriculture Geospatial Data Gateway Web site (U.S. Department of Agriculture, Natural Resources Conservation Service, 2011).

Drilling permits for Marcellus Shale and non-Marcellus Shale natural gas were obtained from the Pennsylvania Department of Environmental Protection Permit and Rig Activity Reports for 2004–2010 (Pennsylvania Department of Environmental Protection, Office of Oil and Gas Management, 2011).

The U.S. Geological Survey (USGS) Watershed Boundary Dataset Hydrologic Unit Code 12-digit (HUC12) for Pennsylvania was downloaded from the USGS National Hydrography Dataset Web site (U.S. Geological Survey, 2011).

The Marcellus Shale Play assessment unit boundaries were downloaded from the USGS Energy Resources Program Data Services Web site (U.S. Geological Survey, 2012).

The 2001 National Land Cover Dataset (NLCD) was acquired for use as the baseline land cover map. The NLCD is a 16-class land cover classification scheme applied consistently across the United States at a 30-meter spatial resolution (Homer and others, 2007). The NLCD may be acquired using the Multi-Resolution Land Characteristics Consortium Web site (U.S. Geological Survey, 2011). The NLCD 2001 was resampled to 10-meter pixel size.

#### Collection

These data were brought into a GIS database for spatial analysis. Using the 2004 imagery as a baseline, the imagery was examined for distinct signs of disturbance related to oil and gas drilling and development. These mapped features include:

- Well Pads - Cleared areas related to existing permits or displaying the characteristics of a shale or coalbed gas extraction site.
- Roads -Vehicular transportation corridors constructed specifically for shale or coalbed gas development.
- Pipelines - New gas pipelines constructed in conjunction with one or more well pads.

- Impoundments - Manmade depressions designed to hold liquid and in support of oil and gas drilling operations.
- Other - Support areas or activities such as processing plants, storage tanks, and staging areas.

The collection of gas extraction infrastructure was a manual process of visually examining high-resolution imagery for each county over four dates to identify and digitize (collect) changes in the land cover resulting from the development of gas extraction infrastructure. Specifically, we examined NAIP 1-meter data composited for the years 2004, 2005/2006, 2008, and 2010, identifying landscape changes that occurred after 2004. See table 1 for dates of acquisition used in each year's composite image.

Changes that correlated with natural gas extraction permits appeared to be natural gas extraction related or were in the proximity of other natural gas extraction infrastructure, and were selected and digitized to the maximum extent of landscape disturbance. The focus of the data collection was on features attributable to the construction, use, and maintenance of gas extraction drill sites, processing plants, and compressor stations, as well as the center lines for new roads accessing such sites, plants, and stations, and the center lines for new pipelines used to transport the extracted gas. Figure 8 shows examples of digitized natural gas extraction features. These data were collected within shapefiles per county, using ArcGIS 10.0 (Esri, Redlands, Calif.). One shapefile was generated for sites (polygons), one was generated for roads (lines), and one was generated for pipelines (lines). Roads and pipelines were generally buffered to 8 and 12 meters, respectively, for overall area assessments. The buffered distance was selected as the average from measurement of roads and pipelines in the counties. All sites were initially classified as gas extraction related or points of interest. Points of interest were unlikely to be related to drilling but were of potential future interest and excluded from further processing. All data collected were reviewed by another team member for concurrence and consistency.

**Table 1.** National Agriculture Image Program (NAIP) dates of acquisition.

| Date of NAIP Mosaic | Dates of collection | | | |
|---|---|---|---|---|
| | Greene County, PA | | Tioga County, PA | |
| 2004 | 11/11/2004 | | 06/12/2004 | 08/24/2004 |
| | | | 09/01/2004 | |
| 2005 | 06/23/2005 | 08/24/2005 | 06/23/2005 | 06/24/2005 |
| | 09/07/2005 | 09/10/2005 | 07/10/2005 | |
| | 09/11/2005 | | | |
| 2008 | 06/07/2008 | 07/02/2005 | 05/29/2005 | 09/05/2008 |
| | 07/15/2005 | 07/18/2005 | 09/19/2008 | 10/07/2008 |
| | 07/29/2005 | 09/03/2005 | | |
| 2010 | 06/08/2010 | 06/18/2010 | 06/02/2010 | 07/05/2010 |
| | 08/31/2010 | 09/02/2010 | 07/07/2010 | 07/11/2010 |
| | | | 09/01/2010 | |

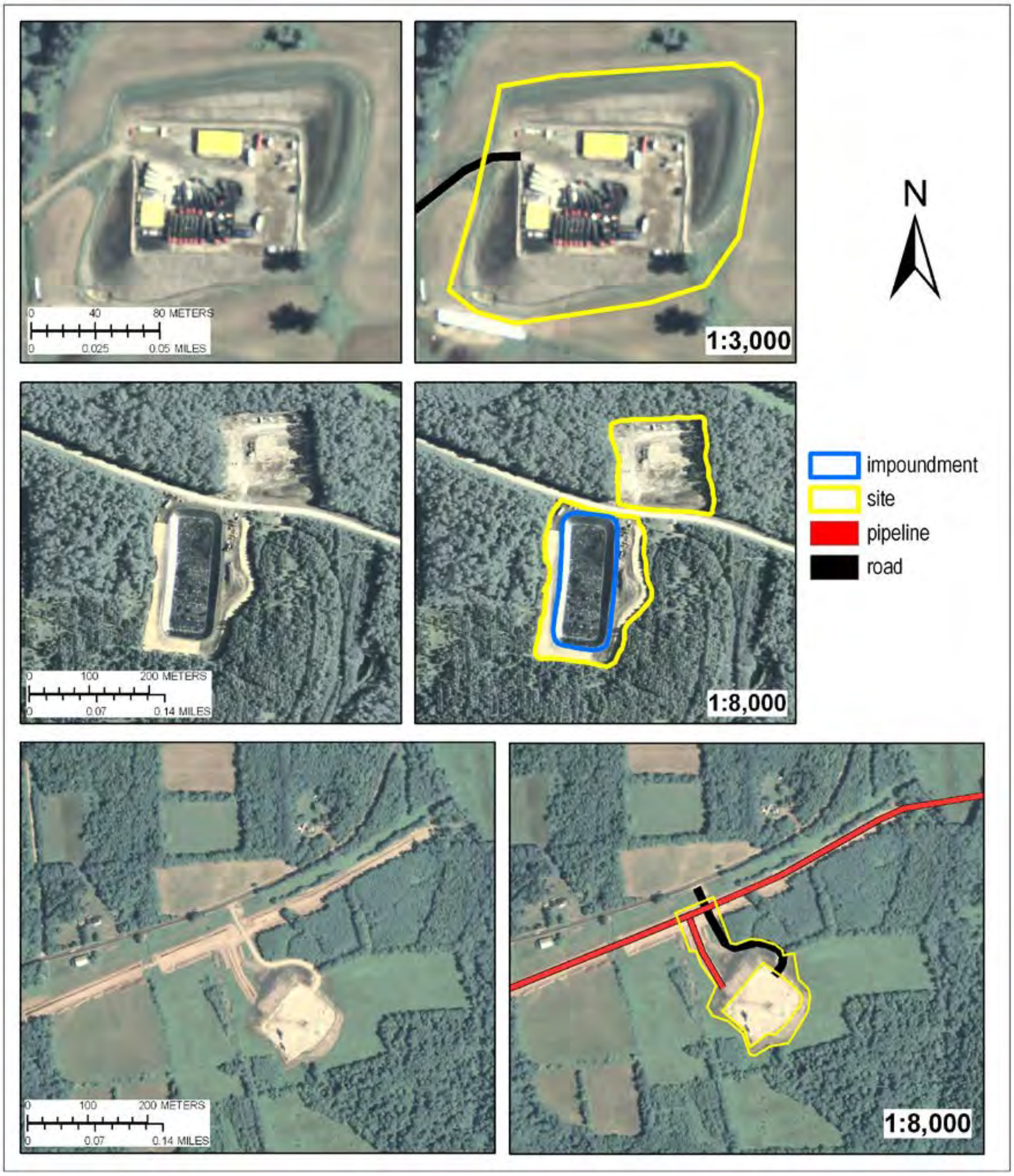

**Figure 8.** Examples of spatially explicit features of disturbance that were extracted from aerial photos into a geographic information systems (GIS) format.

## Land Cover Update

Using the collected and reviewed data, the polygons and line features were processed and aggregated into a raster format used as a mask to update existing land cover data from NLCD 2001. Figure 9 shows the processing flow to accomplish this task consistently across both counties.

Each feature within the shapefiles was processed to determine its permit status and area. Each county's shapefiles were then merged and internal boundaries dissolved resulting in a disturbance footprint for that county. The disturbance footprint was then rasterized and used to conditionally select the pixels in the 2001 NLCD to reclassify as a new class: gas extraction disturbance. To consistently perform this processing, a set of models was developed using the ArcGIS Modelbuilder (Esri, Redlands, Calif.).

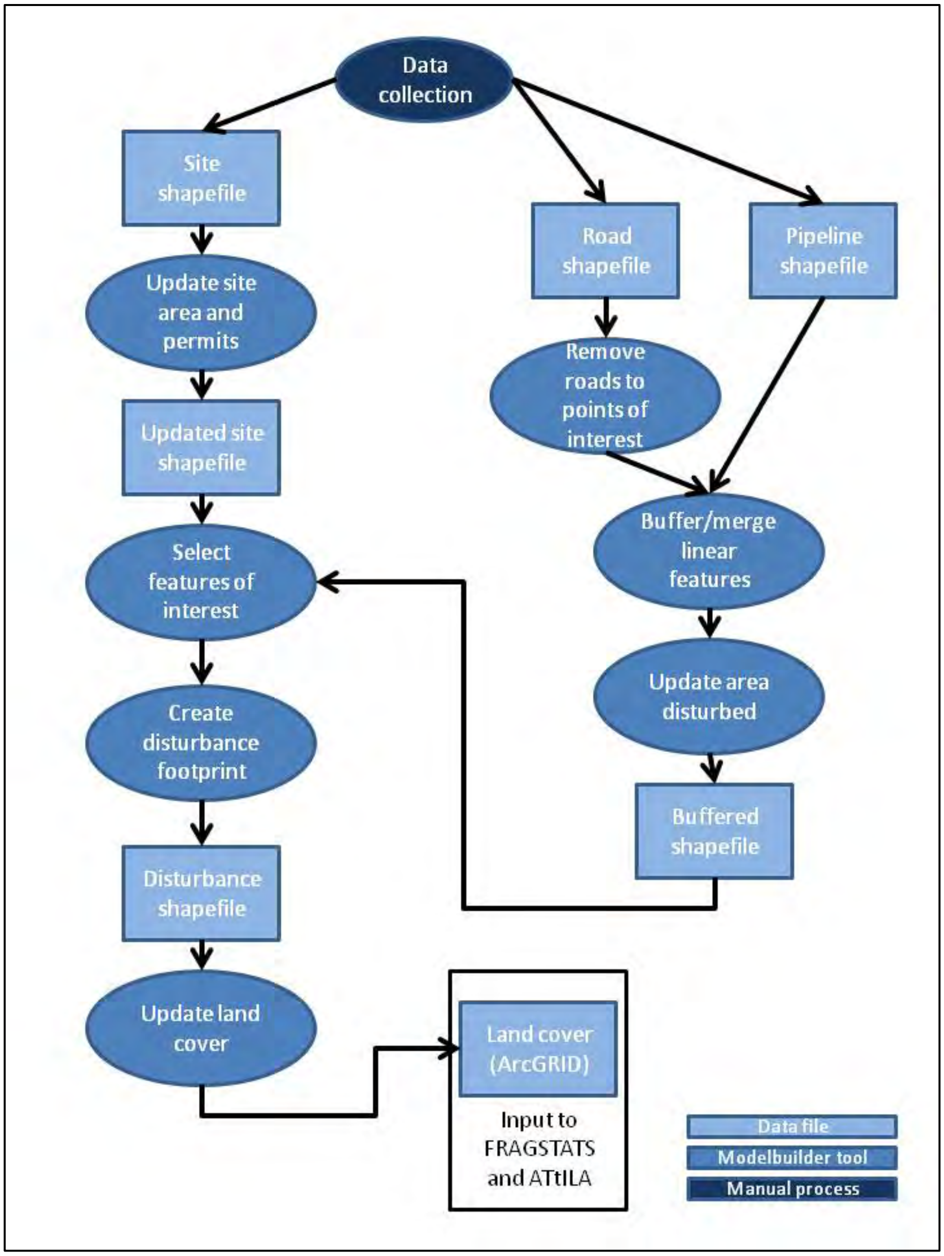

**Figure 9.** Workflow diagram for creating an updated land cover map. The workflow is implemented using ArcGIS model builder automated scripts to process the digitized data and embed in the resampled NLCD 2001.

## Calculation of Landscape Metrics

Landscape-wide and land cover class fragmentation statistics for each county were developed and reported using FRAGSTATS, while land cover class-detailed statistics, forest fragmentation statistics, including patch metrics and forest condition (interior, edge, and so forth) metrics were calculated over smaller watersheds (HUC12) intersecting with the county using ATtILA. The collected statistics were then summarized, charted, and mapped for further analysis.

In addition to the summary of features noted above, a series of landscape metrics was calculated for each county based on the change related to gas development activities between 2004 and 2010. To do this, the metrics were calculated from the 2001 NLCD dataset (Homer and others, 2007). Following that calculation, the 2004–2010 cumulative spatial pattern of disturbance was digitally embedded into the 2001 NLCD dataset and the metrics were recalculated for each county.

## Results: Summary Statistics and Graphics

This section presents a summary of landscape alterations from natural gas resource development, along with the ensuing change in land cover and landscape metrics for each county using metrics suggested by O'Neill and others (1997). These metrics are then calculated and presented based on the sources of that disturbance: Marcellus sites and roads, non-Marcellus sites and roads, and other infrastructure, which includes nonpermitted sites, processing facilities and their associated roads, and pipelines and their associated roads. Nonpermitted sites are defined as disturbed areas that appear to be Marcellus or non-Marcellus gas extraction sites that do not have a permit within 250 meters. These data are presented in tabular form with some graphic presentations provided where appropriate. Examples of the spatial distribution of selected landscape metrics are shown at the watershed level for each county. GIS data of all disturbance features are available upon request.

### Disturbed Area

Documenting the spatially explicit patterns of disturbance was one of the primary goals of this research, and this section describes the extent of disturbed land cover for Greene and Tioga Counties in Pennsylvania. The spatial distribution of disturbance influences the impacts of that disturbance.

In Greene County, the disturbance occurs mostly at the eastern side of the county with some activity at the north and south, and minor activity to the west of the county (fig. 10). Tioga County has less disturbance than Greene County. The disturbance in Tioga County is concentrated in the eastern half and through the central part of the county, almost in a linear fashion, in an east-west direction. The detailed insets in figure 10 show the disturbance footprints in the context of the surrounding land cover.

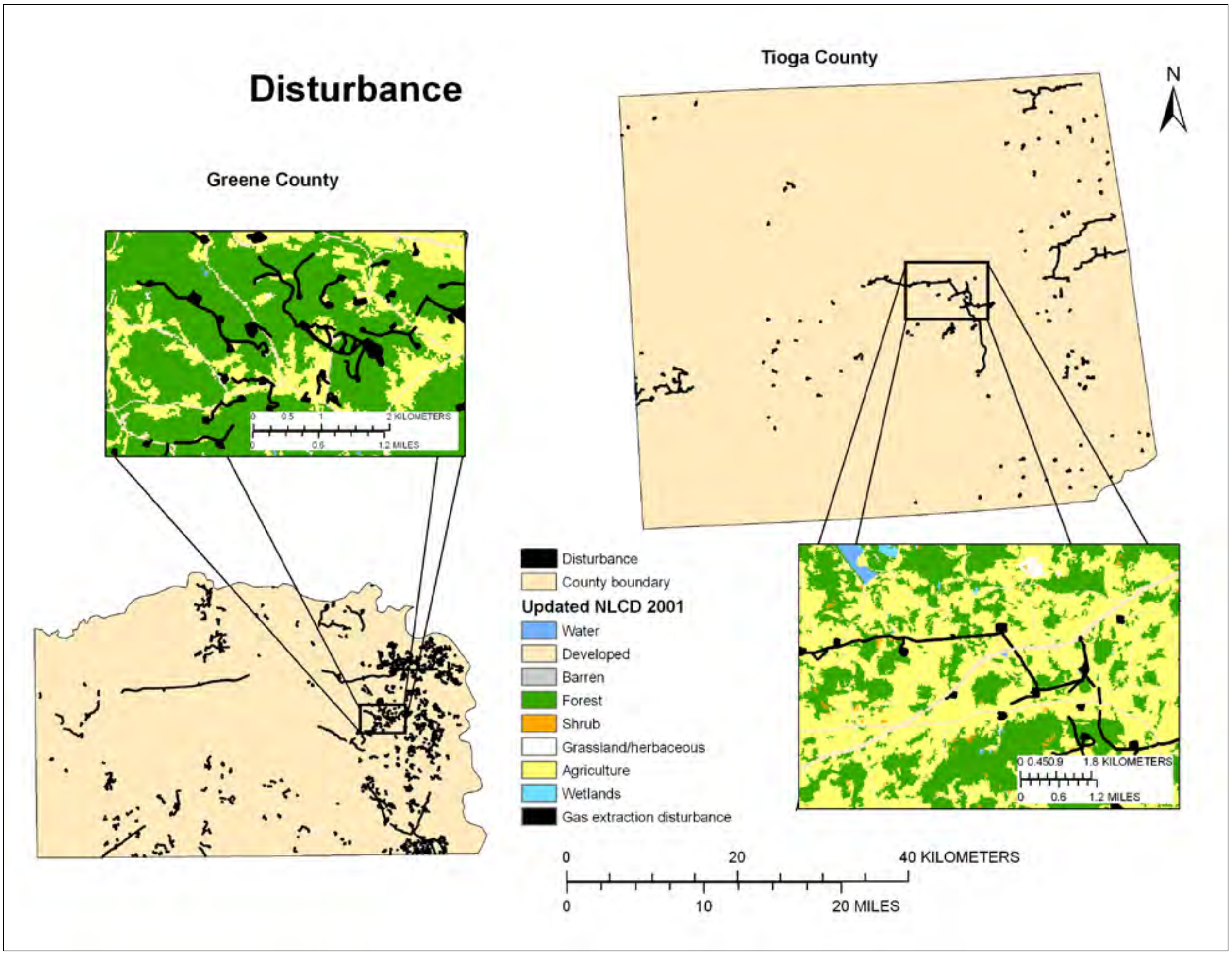

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Greene and Tioga Counties, Pennsylvania. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

Table 2 lists the disturbance area attributable to all sites and impoundments and their associated roads and pipelines. The disturbance area is presented first as a total disturbance for all gas extraction infrastructure including all sites, roads, and pipelines. Total disturbance is broken into two sections: disturbance for all sites and their associated roads and disturbance for pipelines. The disturbance area for all sites and roads is further broken into disturbance for Marcellus Shale sites and roads, non-Marcellus Shale sites and roads, sites with permits for both Marcellus and non-Marcellus drilling, and sites lacking an identifiable permit (for example, processing facilities or incomplete permit data). Additionally, disturbance area associated with impoundments is presented for those impoundments greater than 0.4 hectare and for those less than 0.4 hectare. Because land disturbance or access roads may be associated with multiple infrastructure (for example, pipelines may cross areas also disturbed for drill sites), the values for disturbed areas and road miles within break-out categories such as “MS sites and roads” do not sum up to the higher level category, in this instance “All sites and roads.” The results indicate the following:

- While Tioga County is larger (~730,000 hectares) than Greene County (~370,000 hectares), Greene County has 126 Marcellus and 427 non-Marcellus sites compared to 125 Marcellus and 11 non-Marcellus sites in Tioga County.
- Tioga County has twice the mean hectares of disturbance per site than Greene County (4.0 hectares/sites compared to 2.0 hectares/sites, respectively).
- The mean disturbed hectares for Marcellus sites is almost identical for both counties (2.7 hectares/sites for Greene County and 2.8 hectares/sites for Tioga County), whereas the mean disturbed hectares per non-Marcellus sites is almost three times larger in Tioga County than in Greene County (3.6 hectares/site compared to 1.6 hectares/site, respectively). A visual examination of the Tioga non-Marcellus sites reveals several large sites that include impoundments or multiple wells (both Marcellus and non-Marcellus wells). The larger non-MS sites may use hydraulic fracturing for the extraction of coalbed methane.
- Greene County has almost seven times the number of sites that include processing and transportation facilities and unpermitted sites than Tioga County; however, these sites are about one third the mean size of Tioga County sites (0.9 hectare for Greene County compared to 2.6 hectares for Tioga County).
- Greene County had almost five times the amount of dual sites than Tioga County. The disturbance associated with dual sites was included in the disturbance measures for both Marcellus and non-Marcellus sites.
- Greene County has almost twice the number of impoundments than Tioga County. However, the mean size of large impoundments in Greene County was almost half the mean size of Tioga County (1.1 hectares for Greene versus 1.7 hectares for Tioga), implying a difference in water access, storage, and usage.

**Table 2.** Cumulative amount of landscape disturbance for natural gas extraction development and infrastructure based on disturbance type from 2004 to 2010 by county. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

| Land cover update | Count | Site only hectares | Footprint disturbed hectares | Road kilometers | Pipeline kilometers | Hectares per site | Disturbed hectares per site | Road kilometers per site |
|---|---|---|---|---|---|---|---|---|
| Greene County (370,016 hectares) | | | | | | | | |
| All infrastructure | 663 | 775.6 | 1311.2 | 241.1 | 126.7 | 1.17 | 2.0 | 0.3 |
| All infrastructure | 663 | 775.6 | 1311.2 | 241.1 | 126.7 | 1.17 | 2.0 | 0.3 |
| All sites and roads | 663 | 775.6 | | 241.1 | | | | |
| MS sites and roads | 126 | 270.4 | 341.6 | 56.8 | | 2.14 | 2.7 | 0.5 |
| Non-MS sites and roads | 427 | 457.9 | 680.8 | 174.8 | | 1.1 | 1.6 | 0.5 |
| Other infrastructure\nonpermitted sites and roads | 138 | 122.17 | 332.5 | 63.9 | | 0.9 | 2.4 | 0.3 |
| Dual sites | 28 | 74.9 | | | | 2.7 | | |
| Pipelines | 53 | 304.5 | 288.6 | 33.0 | 126.7 | 5.8 | 5.44 | 0.6 |
| Impoundments (>1 acre) | 32 | 33.5 | | | | 1.1 | | |
| Impoundments (<1 acre) | 119 | 13.9 | | | | 0.1 | | |
| Tioga County (729,701 hectares) | | | | | | | | |
| All infrastructure | 151 | 362.1 | 596.3 | 46.0 | 78.1 | 1.6 | 4.0 | 0.3 |
| All sites and roads | 151 | 362.1 | | 44.4 | | | | |
| MS sites and roads | 125 | 300.2 | 349.6 | 39.3 | | 2.38 | 2.8 | 0.3 |
| Non-MS sites and roads | 11 | 32.17 | 39.9 | 6.0 | | 2.9 | 3.6 | 0.6 |
| Other infrastructure\nonpermitted sites and roads | 20 | 51.6 | 61.1 | 6.9 | | 2.6 | 3.1 | 0.3 |
| Dual sites | 5 | 21.9 | | | | 4.37 | | |

**Table 2.** Cumulative amount of landscape disturbance for natural gas extraction development and infrastructure based on disturbance type from 2004 to 2010 by county. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.—Continued

| Land cover update | Count | Site only hectares | Footprint disturbed hectares | Road kilometers | Pipeline kilometers | Hectares per site | Disturbed hectares per site | Road kilometers per site |
|---|---|---|---|---|---|---|---|---|
| Tioga County (729,701 hectares)—Continued | | | | | | | | |
| Pipelines | 47 | 189.3 | 202.2 | 12.1 | 78.1 | 4.0 | 4.3 | 05.0 |
| Impoundments (>1 acre) | 18 | 30.0 | | | | 1.7 | | |
| Impoundments (<1 acre) | 59 | 7.9 | | | | 0.1 | | |

Land cover change is the initial impact of disturbance and has long-term effects on ecological goods and services. Table 3 lists the percent land cover by county for 2001 and percent land cover and change for the updated 2010 landscape. The land cover change for the updated landscape is further broken into the values attributable to Marcellus sites; non-Marcellus sites; other infrastructure including unpermitted sites; and pipelines, each with their associated roads. Given that the natural land cover of Pennsylvania is forest (Kuchler, 1964), the 2001 land cover provides a measure of the impacts prior to most natural gas resource development; the changes between 2004 and 2010 have only increased these impacts. Of particular interest are the forest cover and its relation to the critical value 59.28 percent from percolation theory (Gardner and others, 1987; O'Neill and others, 1997). Below this value, the forest structure rapidly breaks down into isolated patches, thereby changing forest resilience and habitat corridors. The results indicate the following:

- In both Greene and Tioga Counties, the primary land covers are forest (~72 percent for Greene County and 67 percent for Tioga County), agriculture (17 percent and 25 percent, respectively) and developed (8 percent and 3 percent, respectively). Natural gas resource development had the greatest impact on forest and agricultural land cover.
- Both counties were above 59.28 percent forest in 2001 and forest has been impacted by recent natural gas resource development. Percent forest declined by 0.53 percent (-786 hectares) in Greene County and by 0.08 percent (-225 hectares) in Tioga County.
- In Greene County, forest was the most impacted class by natural gas extraction activities. Of these activities, non-Marcellus sites decreased forest area by 0.26 percent (-392 hectares), followed by Marcellus sites [0.13-percent decrease (-193 hectares)], then pipelines [0.13-percent decrease (-188 hectares)], and other infrastructure [0.10-percent decrease (-144 hectares)]. Agriculture was the second most impacted class by natural gas extraction activities.
- In Tioga County, agriculture was the most affected by natural gas extraction activities. Of these activities, Marcellus sites decreased agriculture areas [0.07-percent decrease
- (-210 hectares)], pipelines [0.03-percent decrease (-99 hectares)], followed by non-Marcellus sites (0.01-percent decrease (-24 hectares)], and other infrastructure (0.01-percent decrease (-16 hectares)]. Forest was the second most impacted class by natural gas extraction. Forest decreased by 116 hectares due to Marcellus sites, 89 hectares due to pipelines, 28 hectares due to other sites, and 14 hectares due to non-Marcellus sites.

**Table 3.** Percent land cover presented in descending order for each county. Change in percent forest is shown in bold. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

| Land cover | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Greene County | | | | | | | | | | | |
| Forest | 72.61 | 72.09 | -0.53 | 72.49 | -0.13 | 72.35 | -0.26 | 72.52 | -0.10 | 72.49 | -0.13 |
| Agriculture | 17.43 | 17.14 | -0.30 | 17.35 | -0.09 | 17.27 | -0.17 | 17.40 | -0.04 | 17.38 | -0.05 |
| Developed | 8.38 | 8.35 | -0.04 | 8.38 | -0.01 | 8.37 | -0.02 | 8.38 | -0.01 | 8.37 | -0.01 |
| Grassland – herbaceous | 0.79 | 0.78 | -0.01 | 0.79 | 0.00 | 0.78 | -0.01 | 0.79 | 0.00 | 0.79 | 0.00 |
| Water | 0.57 | 0.57 | 0.00 | 0.57 | 0.00 | 0.57 | 0.00 | 0.57 | 0.00 | 0.57 | 0.00 |
| Barren | 0.12 | 0.12 | 0.00 | 0.12 | 0.00 | 0.12 | 0.00 | 0.12 | 0.00 | 0.12 | 0.00 |
| Wetlands | 0.07 | 0.07 | 0.00 | 0.07 | 0.00 | 0.07 | 0.00 | 0.07 | 0.00 | 0.07 | 0.00 |
| Scrub – shrub | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 |
| Gas extraction disturbance | | 0.88 | 0.88 | 0.23 | 0.23 | 0.45 | 0.45 | 0.14 | 0.14 | 0.19 | 0.19 |
| Tioga County | | | | | | | | | | | |
| Forest | 67.30 | 67.23 | -0.08 | 67.26 | -0.04 | 67.30 | 0.00 | 67.29 | -0.01 | 67.27 | -0.03 |
| Agriculture | 25.25 | 25.14 | -0.11 | 25.18 | -0.07 | 25.24 | -0.01 | 25.24 | -0.01 | 25.21 | -0.03 |
| Developed | 3.44 | 3.43 | -0.01 | 3.43 | 0.00 | 3.44 | 0.00 | 3.44 | 0.00 | 3.44 | 0.00 |
| Grassland – herbaceous | 0.41 | 0.40 | 0.00 | 0.41 | 0.00 | 0.41 | 0.00 | 0.41 | 0.00 | 0.40 | 0.00 |
| Water | 0.49 | 0.49 | 0.00 | 0.49 | 0.00 | 0.49 | 0.00 | 0.49 | 0.00 | 0.49 | 0.00 |
| Barren | 0.29 | 0.29 | 0.00 | 0.29 | 0.00 | 0.29 | 0.00 | 0.29 | 0.00 | 0.29 | 0.00 |
| Wetlands | 0.46 | 0.46 | 0.00 | 0.46 | 0.00 | 0.46 | 0.00 | 0.46 | 0.00 | 0.46 | 0.00 |
| Scrub – shrub | 2.36 | 2.35 | -0.01 | 2.36 | 0.00 | 2.36 | 0.00 | 2.36 | 0.00 | 2.36 | 0.00 |
| Gas Extraction disturbance | | 0.20 | 0.20 | 0.12 | 0.12 | 0.01 | 0.01 | 0.02 | 0.02 | 0.07 | 0.07 |

## Land Cover Metrics of Interest

There are numerous landscape metrics, many of which are redundant. Table 4 lists the total area, total edge, mean fractal index, contagion and dominance metrics for the 2001 county landscape, and the metrics and change for the updated 2010 landscape. The metrics and change for the updated landscape are further broken into the values attributable to Marcellus sites; non-Marcellus sites; other infrastructure including unpermitted sites; and pipelines, each with their associated roads. These metrics were chosen for their overall indication of human impacts on the landscape and environmental quality (O'Neill and others, 1997). Increase in edge, especially between unlike land covers, indicates declining resilience of the natural land cover and movement of species, while the decrease in the mean fractal index ($1 \leq x \leq 2$) indicates an increase in human use. Evenness ($0 \leq x \leq 1$, where 0 indicates one land cover and 1 indicates even distribution across land cover classes) indicates the relative heterogeneity of the landscape and is the inverse of the dominance measure (McGarigal and others, 2002) recommended by O'Neill and others (1997). Contagion ($0 < x \leq 100$, disaggregated to aggregated) is an indicator that measures the degree of "clumpiness" among the classes of land cover features. The results indicate the following:

- Total edge increased by 858.3 kilometers (533.3 miles) and 306.1 kilometers (190.2 miles) for Greene and Tioga Counties, respectively. The largest amount of change is attributable to non-Marcellus sites in Greene County, whereas in Tioga County, the largest amount of change is attributable to pipeline construction closely followed by Marcellus sites.
- Mean fractal index is intermediate for both counties, reflecting the high percentage (>50 percent) of forest coverage for both Greene and Tioga Counties. Mean fractal index remains unaffected when considering the individual activities (Marcellus sites, non-Marcellus Sites, other infrastructures, and pipelines). Values for mean fractal indexes are similar in both counties (almost identical), and when considering all the natural gas extraction activities, the mean fractal index decreases by 0.0080 in Greene County, while the mean fractal index decreases by 0.0015 in Tioga County.
- Contagion shows a moderate level of clumped land cover. Greene County has a slightly higher level of contagion than Tioga County. The influence of infrastructure type (all, Marcellus, non-Marcellus, other, and pipelines) was similar for Tioga County, but more variable for Greene County. The greatest influence (an increase of 1.0564) on contagion in Greene County was from other infrastructure; the remaining types of infrastructure had similar effects. However, when considering all infrastructure increase in contagion is smaller for both counties (by 0.0491 in Greene County compared with 1.0427 in Tioga County).
- Evenness also shows a moderate level of heterogeneity for both counties with no one land cover dominating. Evenness has similar values for each infrastructure type. Given that the expected land cover is all forest and has an evenness value approaching zero, this value indicates a substantially disturbed landscape.

**Table 4.** Landscape metrics by county. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.
[Note: Categories are not mutually exclusive]

| Metric | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines and roads | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Greene County | | | | | | | | | | | |
| Total area (hectares) | 149,741.06 | 149,741.06 | 0.00 | 149,741.06 | 0.00 | 149,741.06 | 0.00 | 149,740.84 | -0.22 | 149,740.91 | -0.15 |
| Total edge (km) | 14,899.71 | 15,758.03 | 858.32 | 150,52.58 | 152.87 | 153,61.69 | 461.98 | 150,73.65 | 173.94 | 15,179.05 | 279.34 |
| Mean fractal index | 1.1385 | 1.1305 | -0.0080 | 1.1363 | -0.0022 | 1.1340 | -0.0045 | 1.1369 | -0.0016 | 1.1361 | -0.0024 |
| Contagion | 74.6844 | 74.7335 | 0.0491 | 75.6465 | 0.9621 | 75.2797 | 0.5953 | 75.7408 | 1.0564 | 75.6395 | 0.9551 |
| Evenness | 0.4974 | 0.4993 | 0.0019 | 0.4921 | -0.0053 | 0.4945 | -0.0029 | 0.4913 | -0.0061 | 0.4919 | -0.0055 |
| Tioga County | | | | | | | | | | | |
| Total area | 295,300.80 | 295,300.80 | 0.00 | 295,300.80 | 0.00 | 295,300.80 | 0.00 | 295,300.80 | 0.00 | 295,300.80 | 0.00 |
| Total edge (km) | 20,470.87 | 20,776.97 | 306.10 | 20,606.58 | 135.71 | 20,488.05 | 17.18 | 20,494.67 | 23.80 | 20,654.30 | 183.43 |
| Mean fractal index | 1.1265 | 1.1250 | -0.0015 | 1.1258 | -0.0007 | 1.1264 | -0.0001 | 1.1263 | -0.0002 | 1.1257 | -0.0008 |
| Contagion | 73.9657 | 75.0084 | 1.0427 | 75.1473 | 1.1816 | 75.3287 | 1.3630 | 75.3175 | 1.3518 | 75.2027 | 1.2370 |
| Evenness | 0.5502 | 0.5434 | -0.0068 | 0.5426 | -0.0076 | 0.5418 | -0.0084 | 0.5418 | -0.0084 | 0.5423 | -0.0079 |

## Forest Fragmentation

Disturbance in the landscape will affect forests by fragmentation, which is the process of dividing large land cover (for example, forest) into smaller segments called patches. A patch is defined as adjacent (forest) pixels, including diagonals. A landscape with many small patches is representative of a highly fragmented landscape. Fragmented forests provide habitat for edge species, but are poor for interior species, and are less likely to provide migration corridors.

Fragmentation may be evaluated by change in the number of patches, and change in the mean and (or) median patch size. Table 5 compares the changing forest patch metrics for the 2001 land cover, the updated 2010 land cover, and subsets of the updated 2010 land cover based on Marcellus infrastructure, non-Marcellus infrastructure, other infrastructure, and pipelines. The results indicate the following:

- Forests became more fragmented due to natural gas resource development. Both Greene and Tioga Counties contained more, but smaller forest patches in 2010 than in 2001.
- Greene County forest patches increased by 600 patches; most (~324 patches) are attributable to non-Marcellus sites. These patches initially averaged over 75 hectares, but that average was reduced by about 14 hectares in 2010.
- Tioga County forest patches increased by almost 213 patches; most (~151 patches) are attributable to pipeline construction. These patches initially averaged about 65 hectares and were reduced by about 4 hectares to a mean of about 60 hectares. Marcellus sites and pipelines had the greatest effect on these values.
- The mean patch area in Greene County was greatly reduced for Greene County due to natural gas extraction activities—22.8 hectares in Greene County, compared to a decrease in mean forest patch area of ~-4.0 hectares in Tioga County.
- The reduction in mean forest patch area can be attributable to non-Marcellus sites in Greene County, whereas in Tioga County it can be attributable to pipeline construction.

**Table 5.** Forest fragmentation metrics by county. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.
[Note: Categories are not mutually exclusive]

| Distribution statistics | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Greene County** | | | | | | | | | | | |
| Number of patches | 1,434.00 | 2,034.00 | 600.00 | 1,550.00 | 116.00 | 1,758.00 | 324.00 | 1,539.00 | 105.00 | 1,605.00 | 171.00 |
| Forest patch area mean (hectares) | 75.83 | 53.07 | -22.75 | 70.03 | -5.80 | 61.63 | -14.20 | 70.56 | -5.27 | 67.63 | -8.20 |
| Forest patch area median (hectares) | 0.54 | 0.43 | -0.11 | 0.53 | -0.01 | 0.45 | -0.09 | 0.53 | -0.01 | 0.53 | -0.01 |
| **Tioga County** | | | | | | | | | | | |
| Number of patches | 3,079.00 | 3,292.00 | 213.00 | 3,143.00 | 64.00 | 3,083.00 | 4.00 | 3,088.00 | 9.00 | 3,230.00 | 151.00 |
| Forest patch area mean (hectares) | 64.55 | 60.31 | -4.25 | 63.20 | -1.35 | 64.46 | -0.09 | 64.35 | -0.20 | 61.51 | -3.05 |
| Forest patch area median (hectares) | 0.89 | 0.81 | -0.08 | 0.83 | -0.06 | 0.89 | 0.00 | 0.89 | 0.00 | 0.82 | -0.07 |

Figure 11 illustrates the spatial distribution of the change in the number of forest patches by watershed. Note the relation between disturbance and the change in the number of forest patches. The increase of more than 50 forest patches in some watersheds indicates an increasingly fragmented landscape with habitat implications for many species.

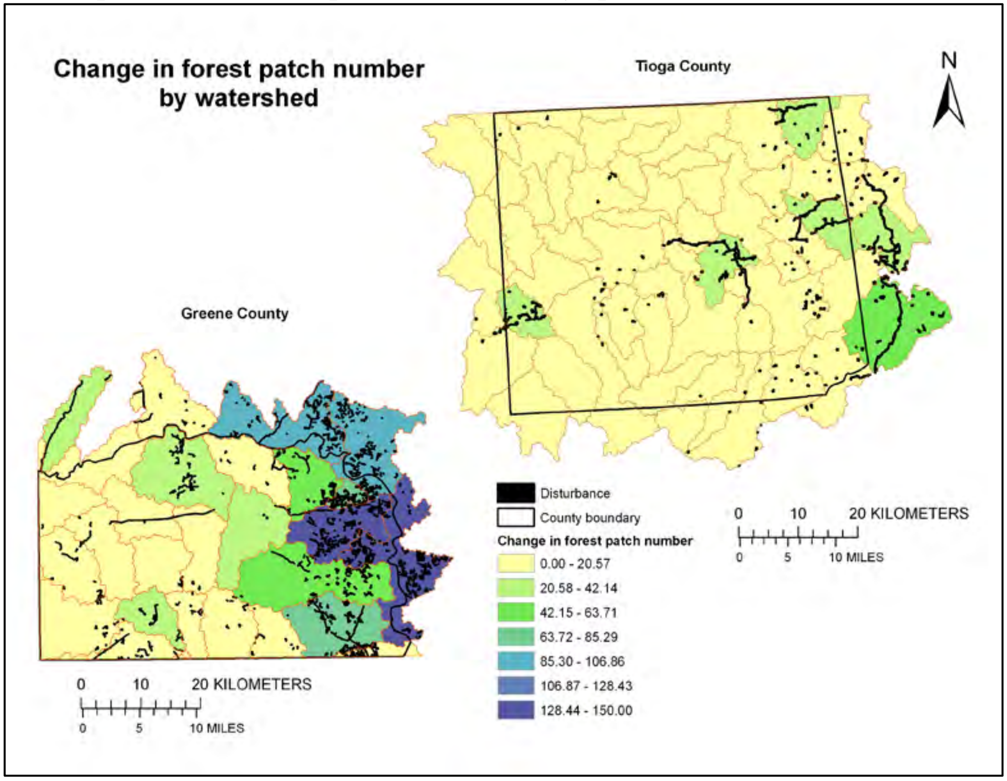

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing the increasing fragmentation in Green and Tioga Counties, Pennsylvania. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## Interior and Edge Forest

Forest condition (interior and edge) is another way to evaluate the state of the forest. In particular, interior forest is subject to more rapid decline than other segments of the forest. Table 6 shows the change in interior forest and edge forest based on natural gas resource development and the types of natural gas extraction infrastructure. Figures 12 and 13, respectively, illustrate the spatial distribution by watershed of change in percent interior forest and the spatial distribution of change in percent edge forest. The results indicate the following:

- Greene County lost 0.53 percent forest, which contributed to a 1.40-percent loss of interior forest and a gain of 0.65 percent in edge forest.
- Tioga County lost 0.08 percent forest, which contributed to a 0.15-percent loss of interior forest and a gain of 0.06 percent in edge forest.
- Forest loss in Greene County was mainly attributable to non-Marcellus sites, while Marcellus sites and pipelines were the major contributors for forest loss in Tioga County.
- A tentative pattern that appears is that the interior forest loss is approximately twice that of the overall forest loss, and the gain in edge forest approximates that overall forest loss.

**Table 6.** Change in percent interior forest and percent edge forest by county. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

[Note: Categories are not mutually exclusive]

| Distribution statistics | Original land cover | Updated with all infra-structure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infra-structure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Greene County | | | | | | | | | | | |
| Number of patches | 1,434.00 | 2,034.00 | 600.00 | 1,550.00 | 116.00 | 1,758.00 | 324.00 | 1,539.00 | 105.00 | 1,605.00 | 171.00 |
| Percent forest | 73.03 | 72.50 | -0.53 | 72.90 | -0.13 | 72.77 | -0.26 | 72.94 | -0.10 | 72.90 | -0.13 |
| Percent interior forest | 47.54 | 46.14 | -1.40 | 47.27 | -0.27 | 46.79 | -0.75 | 47.22 | -0.32 | 47.10 | -0.44 |
| Percent edge forest | 19.46 | 20.11 | 0.65 | 19.55 | 0.09 | 19.81 | 0.35 | 19.62 | 0.16 | 19.70 | 0.24 |
| Tioga County | | | | | | | | | | | |
| Number of patches | 3,079.00 | 3,292.00 | 213.00 | 3,143.00 | 64.00 | 3,083.00 | 4.00 | 3,088.00 | 9.00 | 3,230.00 | 151.00 |
| Percent forest | 67.64 | 67.56 | -0.08 | 67.60 | -0.04 | 67.63 | 0.00 | 67.63 | -0.01 | 67.61 | -0.03 |
| Percent Interior forest | 52.72 | 52.57 | -0.15 | 52.66 | -0.07 | 52.71 | -0.01 | 52.70 | -0.02 | 52.64 | -0.09 |
| Percent edge forest | 10.83 | 10.89 | 0.06 | 10.85 | 0.02 | 10.83 | 0.00 | 10.84 | 0.01 | 10.88 | 0.05 |

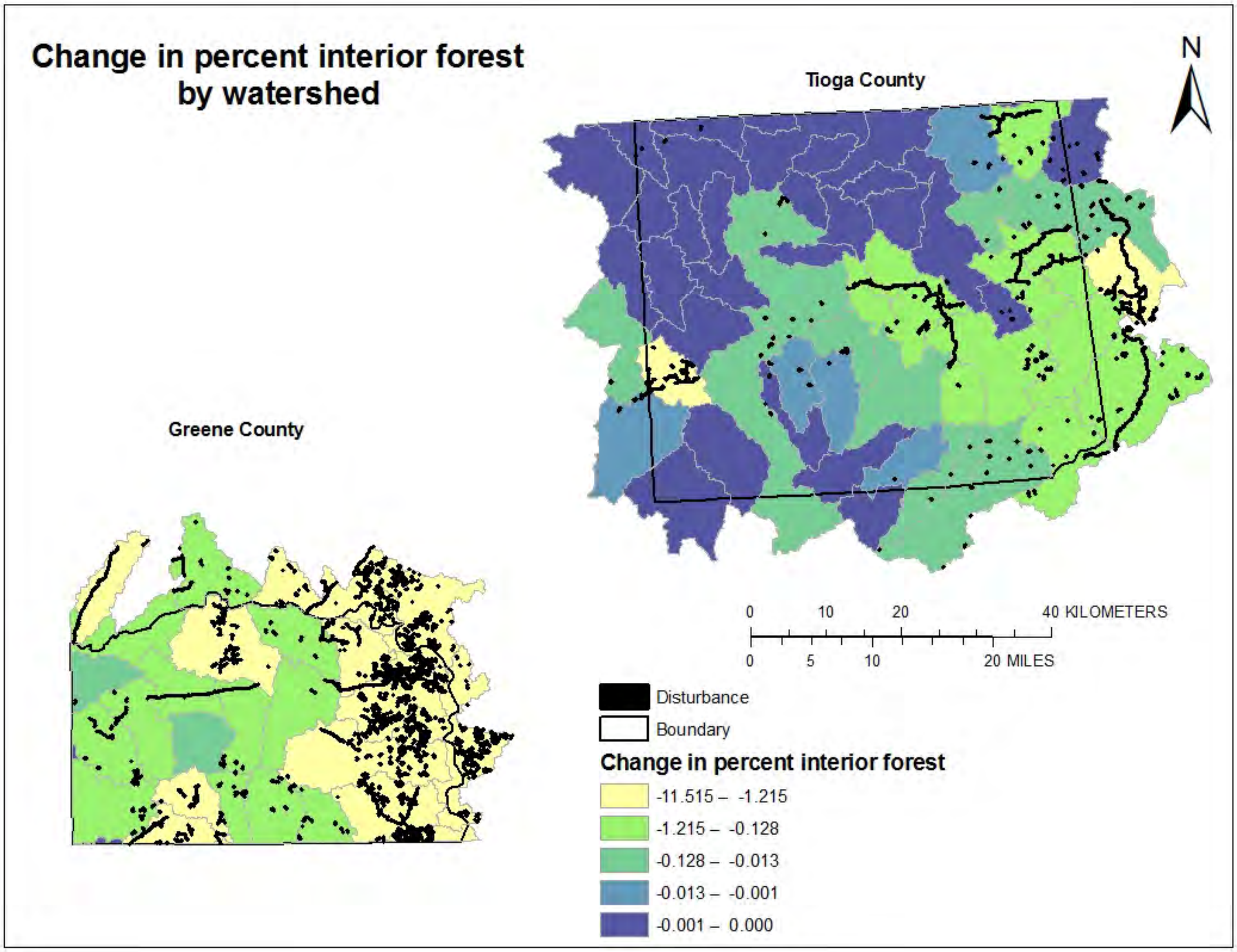

**Figure 12.** Change in percent interior forest in Greene and Tioga Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

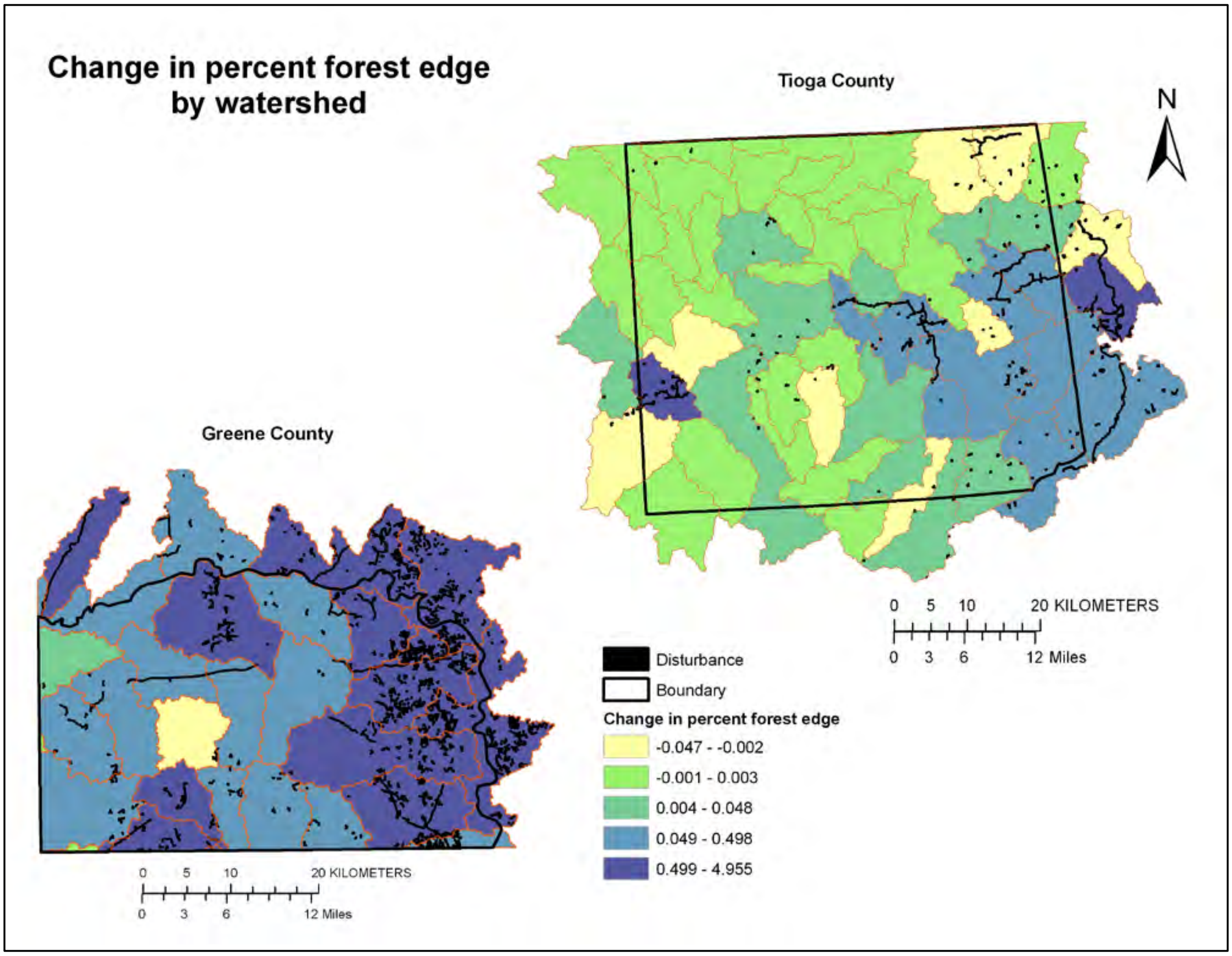

**Figure 13.** Change in percent of edge forest in Greene and Tioga Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## Conclusion

The results presented here document several landscape metrics that show how natural gas extraction in Pennsylvania is affecting the landscape configuration. Agricultural and forested areas are being disturbed by natural gas exploration, development and extraction. The disturbance and effects of both Marcellus and non-Marcellus development are clearly different over both counties; Greene County has higher activity (Marcellus and non-Marcellus) than Tioga County. The effects of non-Marcellus sites are greater in Greene County than in Tioga County, where Marcellus sites activities predominate over non-Marcellus sites.

The fractal dimension, contagion, and dominance were reported based on the recommendations of O'Neill and others (1997); however, they do not appear to be important in these counties. They may be of greater importance for other counties and are reported here for consistency.

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# Landscape Consequences of Natural Gas Extraction in Bradford and Washington Counties, Pennsylvania, 2004–2010

By E.T. Slonecker, L.E. Milheim, C.M. Roig-Silva, A.R. Malizia, D.A. Marr, and G.B. Fisher

Open-File Report 2012–1154

**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
KEN SALAZAR, Secretary

**U.S. Geological Survey**
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

Suggested citation:
Slonecker, E.T., Milheim, L.E., Roig-Silva, C.M., Malizia, A.R., Marr, D.A., and Fisher, G.B., 2012, Landscape consequences of natural gas extraction in Bradford and Washington Counties, Pennsylvania, 2004–2010: U.S. Geological Survey Open-File Report 2012–1154, 36 p.

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# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| Length | | |
| mile (mi) | 1.609 | kilometer (km) |
| Area | | |
| acre | 4,047 | square meter (m2) |
| acre | 0.4047 | hectare (ha) |

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| Length | | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| Area | | |
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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## Abstract

Increased demands for cleaner burning energy, coupled with the relatively recent technological advances in accessing unconventional hydrocarbon-rich geologic formations, led to an intense effort to find and extract natural gas from various underground sources around the country. One of these sources, the Marcellus Shale, located in the Allegheny Plateau, is undergoing extensive drilling and production. The technology used to extract gas in the Marcellus Shale is known as hydraulic fracturing and has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on water resources. Nonetheless, development of natural gas extraction wells in the Marcellus Shale is only part of the overall natural gas story in the area of Pennsylvania. Coalbed methane, which is sometimes extracted using the same technique, is often located in the same general area as the Marcellus Shale and is frequently developed in clusters across the landscape. The combined effects of these two natural gas extraction methods create potentially serious patterns of disturbance on the landscape. This document quantifies the landscape changes and consequences of natural gas extraction for Bradford County and Washington County, Pennsylvania, between 2004 and 2010. Patterns of landscape disturbance related to natural gas extraction activities were collected and digitized using National Agriculture Imagery Program (NAIP) imagery for 2004, 2005/2006, 2008, and 2010. The disturbance patterns were then used to measure changes in land cover and land use using the National Land Cover Database (NLCD) of 2001. A series of landscape metrics is used to quantify these changes and are included in this publication.

## Introduction: Natural Gas Extraction

The need for cleaner burning energy, coupled with the relatively recent technological advances in accessing hydrocarbon-rich geologic formations, has led to an intense effort to find and extract natural gas from various underground sources around the country. One of these formations, the Marcellus Shale, is currently the target of extensive drilling and production in the Allegheny Plateau, extending generally from New York to West Virginia as shown in figure 1 (Coleman and others, 2011). Coleman and others (2011) defined assessment units (AU) of Marcellus Shale production based on the geology of the region.

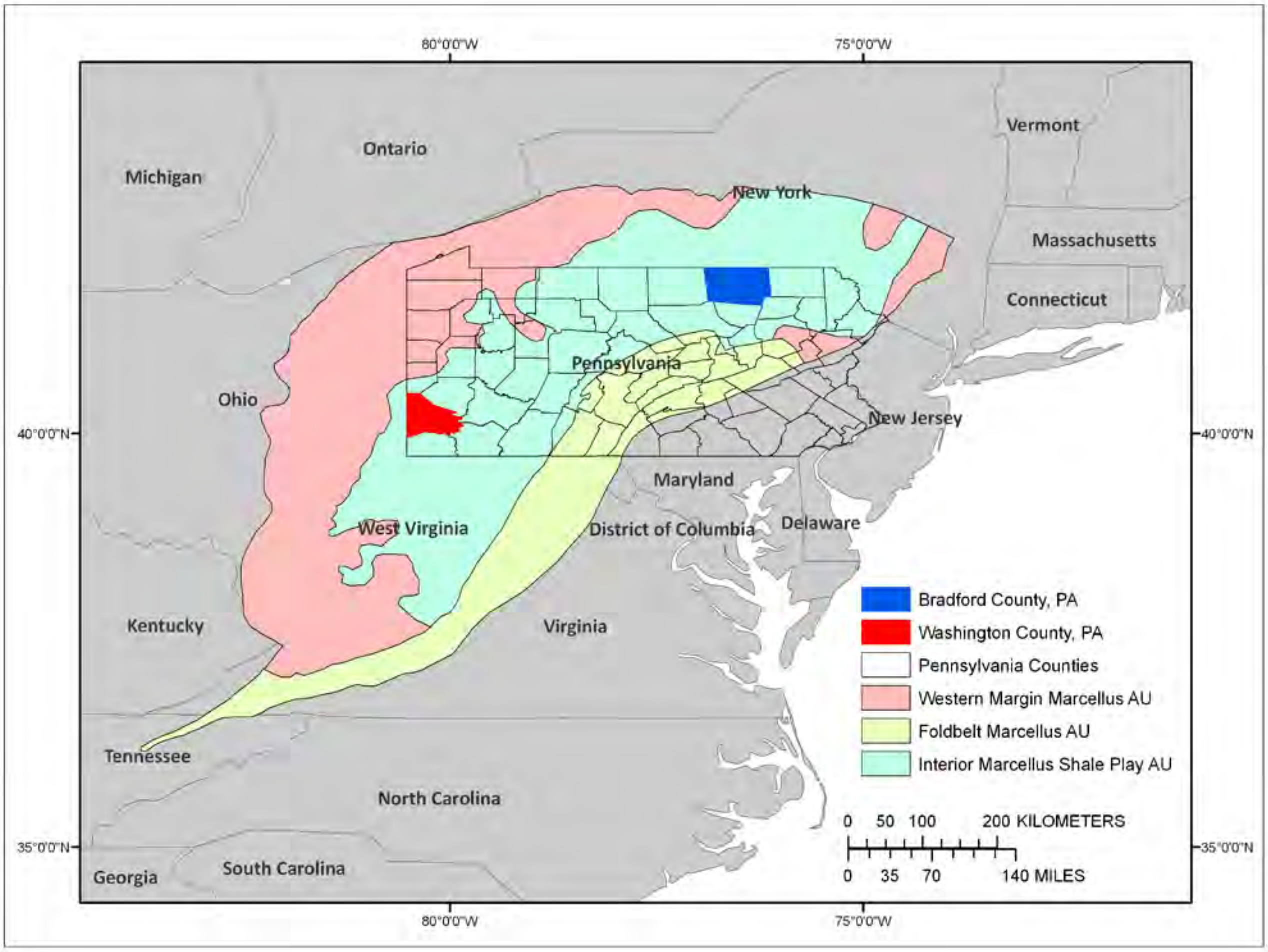

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus Shale AU is expected to be a major production area for natural gas (Coleman and others, 2011). Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

The overall landscape effects of natural gas development have been substantial. Over 9,600 Marcellus Shale gas drilling permits and over 49,500 non-Marcellus Shale permits have been issued from 2000 to 2011 in Pennsylvania (Pennsylvania Department of Environmental Protection, 2011) and over 2,300 Marcellus Shale permits in West Virginia (West Virginia Geological and Economic Survey, 2011), with most of the development activity occurring since 2005.

The Marcellus Shale is generally located 600 to 3,000 meters below land surface (Coleman and others, 2011). Gas and petroleum liquids are produced with a combination of vertical and horizontal drilling techniques, coupled with a process of hydraulically fracturing the shale formation, known as "fracking," which releases the natural gas.

The hydraulic-fracturing process has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids for the hydraulic-fracturing process, its potential to release contaminants into the environment, and its potential effect on groundwater and drinking-water resources.

However, with all of the development of natural gas wells in the Marcellus Shale, it is only part of the overall natural gas story in this area. Coalbed methane, which is extracted in similar wells, is often located in the same general area as the Marcellus Shale. The coalbed methane wells are much shallower and less productive than the Marcellus natural gas wells, but are often located in clusters that dot large areas of the landscape, with nearly 60,000 total gas wells. There may be both types of wells affecting a given area. With the accompanying areas of disturbance, well pads, new roads, and pipelines from both types of natural gas wells, the effect on the landscape is often dramatic. Figure 2 shows a pattern of landscape change from forest to forest, interspersed with gas extraction infrastructure. These landscape effects have consequences for the ecosystems, wildlife, and human populations that are colocated with natural gas extraction activities. This document examines the landscape consequences of gas extraction for two areas of current Marcellus Shale and non-Marcellus Shale natural gas extraction activity.

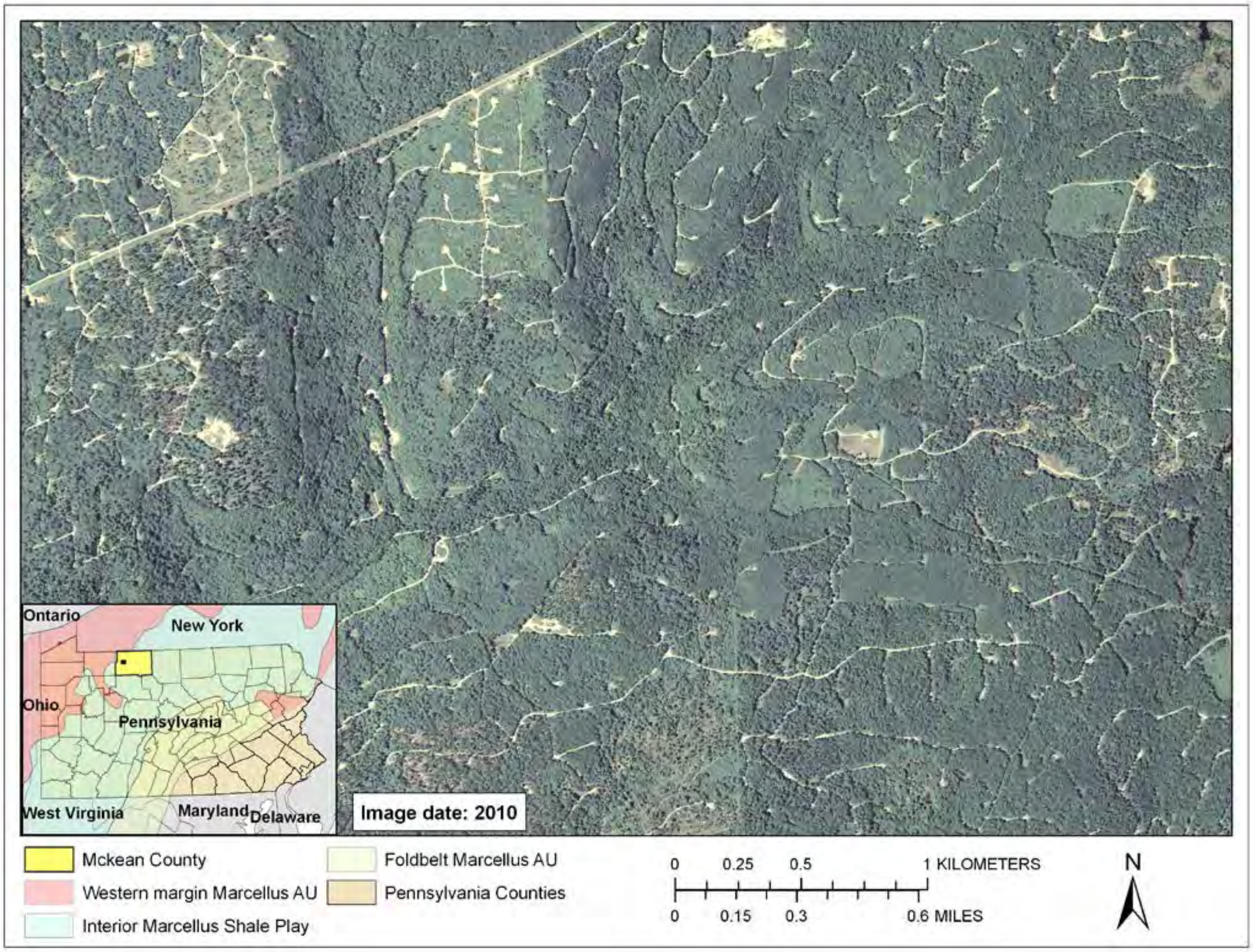

**Figure 2.** A forested landscape in McKean County, Pennsylvania, showing the spatial effects of roads, well pads, and pipelines related to natural gas development. Inset shows the location of the image. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## Location

This assessment of landscape effects focuses on two counties involved in the Marcellus Shale area of development known as the “Play”—Bradford County and Washington County in Pennsylvania. These counties were chosen for their position within the “sweet spots” of exceptionally productive Marcellus Shale (Stevens and Kuuskraa, 2009). Figure 3 below identifies the selected counties in relation to the Marcellus Shale Play and the distribution of Marcellus and non-Marcellus gas extraction permits granted by Pennsylvania.

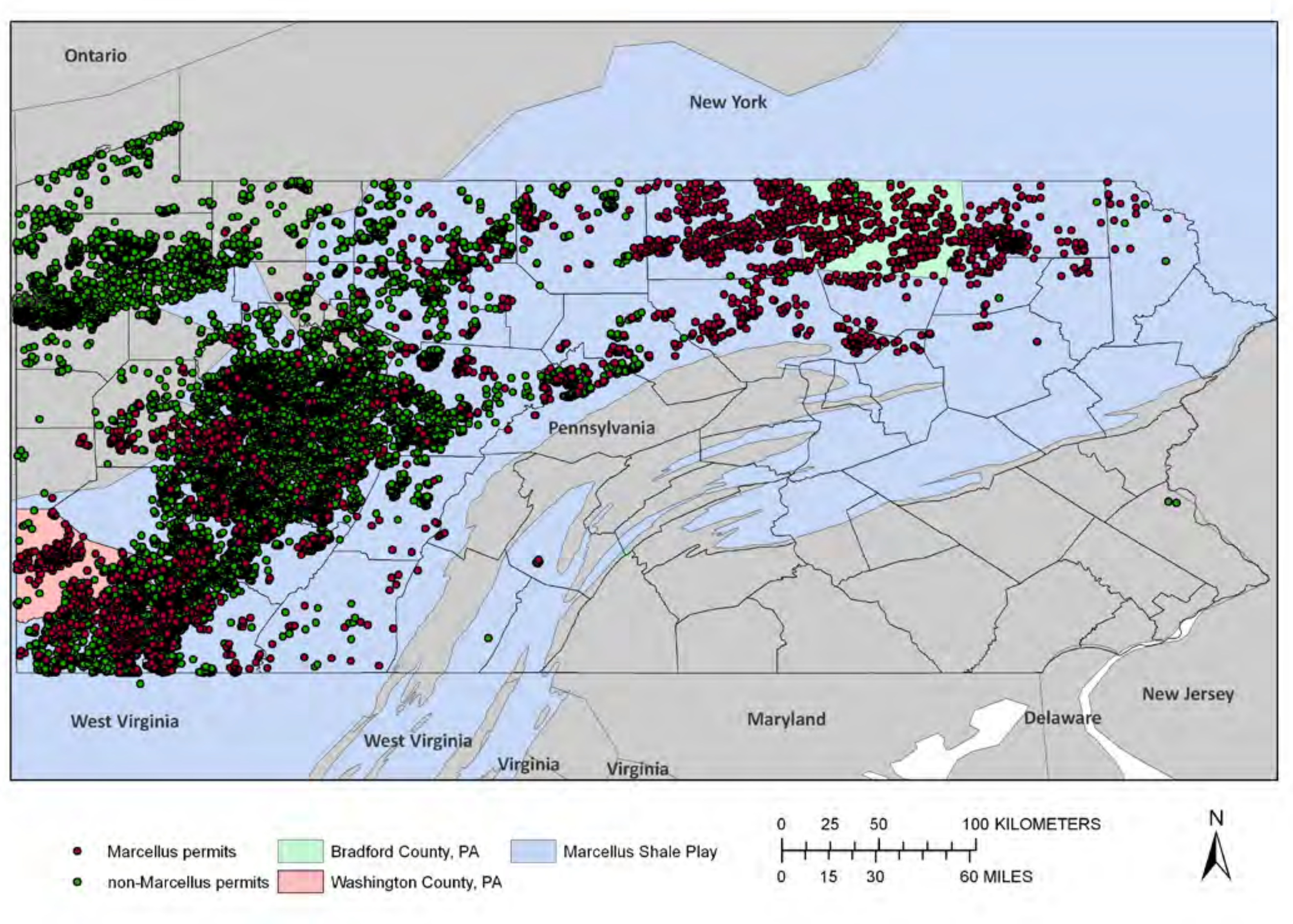

**Figure 3.** The distribution of Marcellus and non-Marcellus natural gas permits within Pennsylvania, the focal counties of Bradford and Washington, and their relation to the Marcellus Shale Play Interior assessment unit. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## The Biogeography of Pennsylvania Forests

Forests are a critical land cover in Pennsylvania. Prior to the European settlements, Pennsylvania was almost completely forested and even today, with modern agriculture, urban growth, and population growth, Pennsylvania is still roughly 60 percent forested. Pennsylvania forests of the 17th century were diverse but were dominated by beech and hemlock, which composed 65 percent of the total forest

(Pennsylvania Department of Conservation and Natural Resources, 2011). However, in the late 19th century, Pennsylvania became the country’s leading source of lumber, in which a number of products, from lumber to the production of tannic acid, were generated from the forestry industry (Pennsylvania Department of Conservation and Natural Resources, 2011). By the early 20th century, most of Pennsylvania’s forests had been harvested. Soon after most of the trees were felled, wildfires, erosion, and flooding became prevalent, especially in the Allegheny Plateau region (Pennsylvania Parks and Forests Foundation, 2010).

The 20th century saw resurgence in Pennsylvania forests. The Weeks Act of 1911 authorized the Federal purchase of forest land on the headwaters of navigable rivers to control the flow of water downstream and act as a measure of flood control for the thriving steel industry of Pittsburgh. Slowly, the forests began to grow back but with a vastly different composition composed of black cherry, red maple, and sugar maple species (Pennsylvania Parks and Forests Foundation, 2010). For the most part, except for a very few isolated areas in north central Pennsylvania and some State parks, the majority of forest cover is currently of the new composition and not of virgin forest. Figure 4 shows that today the concentrations of forests in Pennsylvania are highest in the central and north-central parts of the State, which is also the main area of hydraulic-fracturing activity in the Marcellus Shale.

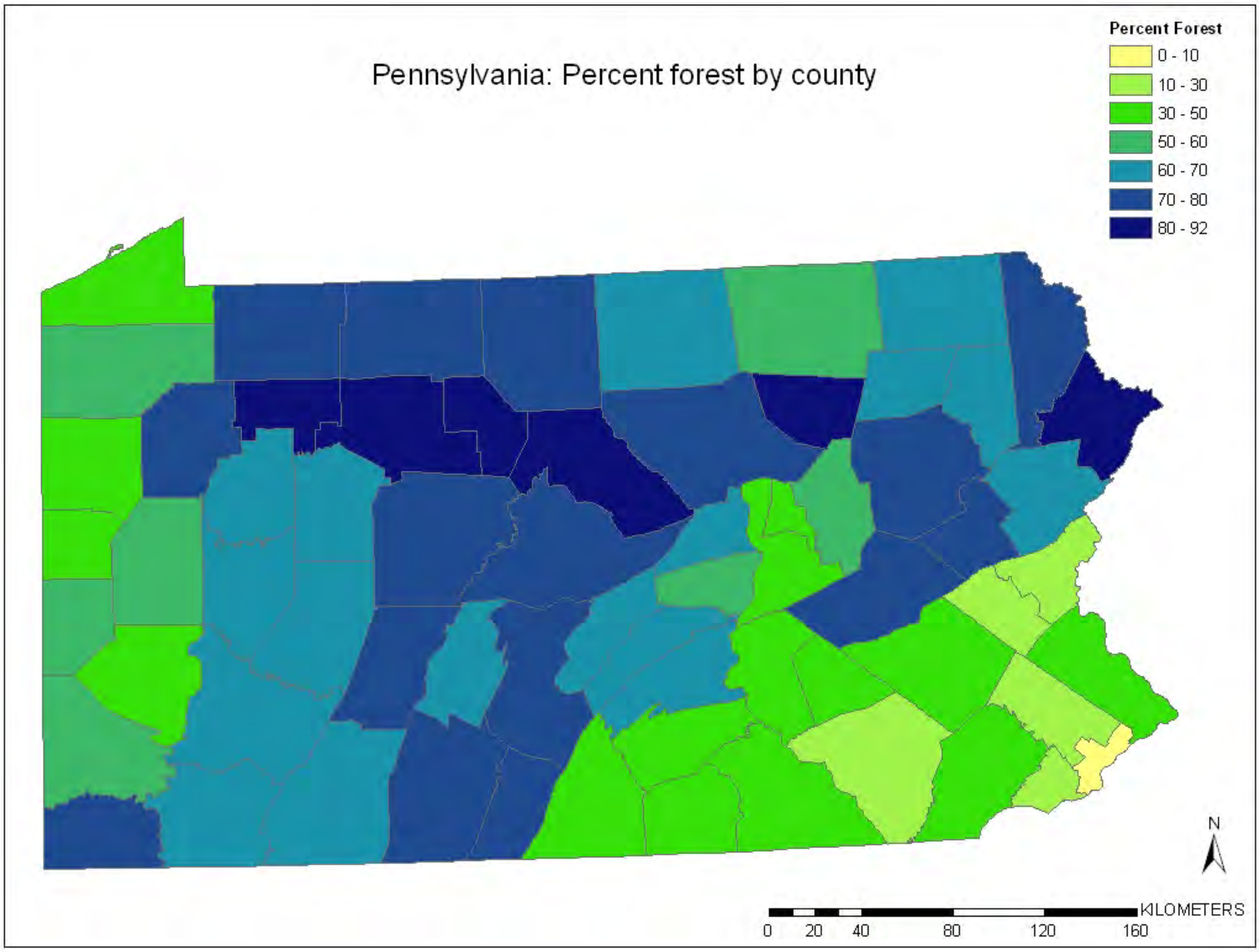

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Data. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

Pennsylvania forests provide critical habitat to a number of plant species, such as the sugar maple, the Eastern red cedar, and evergreens, which produce berries in the winter. There were a number of species that have been eradicated from the region such as moose, North American cougar, bison, and grey wolf (Nilsson, 2005). Today, animal species range from the typical skunk to flying squirrels and multiple different varieties of snakes and bats. However, a diverse population of birds depends on the forests for survival. In the State of Pennsylvania, there are 394 different bird species that are native, including endangered species such as the peregrine falcon and the bald eagle (Gross, 2005).

## Key Research Questions

One key aspect of this research is to quantify the level of disturbance in terms of land use and land cover change by specific disturbance category (well pads, roads, pipelines, and so forth). This quantification will be accomplished by extracting the signatures of disturbance from high-resolution aerial images and then computing landscape metrics in a geographic information systems (GIS) environment.

This research and monitoring effort will attempt to answer the following key research questions:

- What is the level of overall disturbance attributed to gas exploration and development activities and how has this changed over time?
- What are the structural components (land cover classes) of this change and how much change can be attributed to each class?
- How has the disturbance associated with natural gas exploration and development affected the structure, pattern, and process of key ecosystems, especially forests, within the Marcellus Shale Play?
- How will the disturbance stressors affect ecosystem structure and function at a landscape and watershed scale?

## Landscape Metrics and a Landscape Perspective

An important and sometimes overlooked aspect of contemporary gas exploration activity is the geographic profile and spatial arrangement of these activities on the land surface. The function of ecosystems and the services they provide are due in large part to their spatial arrangement on the landscape. Energy exploration and development represents a specific form of land use and land cover change (LULCC) activity that substantially alters certain critical aspects of the spatial pattern, form, and function of landscape interactions.

Changes in land use and land cover affect the ability of ecosystems to provide essential ecological goods and services, which, in turn, affect the economic, public health, and social benefits that these ecosystems provide. One of the great scientific challenges for geographic science is to understand and calibrate the effects of land use and land cover change and the complex interaction between human and biotic systems at a variety of natural, geographic, and political scales (Slonecker and others, 2010).

Land use and land cover change, such as the disturbance and the landscape effects of energy exploration, is currently occurring at a relatively rapid pace prompting immediate scientific focus and attention. Understanding the dynamics of land surface change requires an increased understanding of the complex nature of human-environmental systems and requires a suite of scientific tools that include traditional geographic data and analysis methods, such as remote sensing and GIS, as well as innovative approaches to understanding the dynamics of complex natural systems (O’Neill and others, 1997; Turner, 2005; Wickham and others, 2007). One such approach that has gained much recent scientific attention is the landscape indicator, or landscape assessment, approach, which has been developed with the science of landscape ecology (O’Neill and others, 1997).

Landscape assessment utilizes spatially explicit imagery and GIS data on land cover, elevation, roads, hydrology, vegetation, and in situ sampling results to compute a suite of numerical indicators known as **landscape metrics** to assess ecosystem condition. Landscape analysis is focused on the relation between pattern and process and broad-scale ecological relationships such as habitat, conservation, and sustainability. Landscape analysis necessarily considers both biological and socioeconomic issues and relationships. This research explores these relationships and their potential effect on various ecosystems and biological endpoints.

The landscape analysis presented here is based largely on the framework outlined in O’Neill and others (1997). There are many landscape metrics that can be computed and utilized for some analytical purpose. However, it has been shown by several researchers (Wickham and Riitters, 1995; Riitters and others, 1995; Wickham and others, 1997) that many of these metrics are highly correlated, sensitive to misclassification and pixel size, and, to some extent, questionable in terms of additional information value. The key landscape concepts and metrics reported here are discussed below. The actual formulae used to compute these specific metrics can be found in software documentation for FRAGSTATS and ATtILA (McGarigal and others, 2002; Ebert and Wade, 2004). Computation details for percent interior forest and percent edge forest are documented by Riitters and others (2000).

The concept of landscape metrics, sometimes called landscape indices, is derived from the emerging field of landscape ecology and is rooted in the realization that pattern and structure are important components of ecological process. Landscape metrics are spatial/mathematical indices that have been developed that allow the objective description of different aspects of landscape structures and patterns (McGarigal and others, 2002). They characterize the landscape structure and various processes at both landscape and ecosystem level. Metrics such as average patch size, fragmentation, and interior forest dimension capture spatial characteristics of habitat quality and potential change effects on critical animal and vegetation populations.

Two different geostatistical landscape analysis programs were used to measure the landscape metrics presented in this report. FRAGSTATS (University of Massachusetts, Amherst, Mass.) is a spatial pattern analysis program for quantifying numerous landscape metrics and their distribution, and is available at: *http://www.umass.edu/landeco/research/fragstats/fragstats.html* (McGarigal and others, 2002). ATtILA (Analytical Tools Interface for Landscape Assessments) (U.S. Environmental Protection Agency, Las Vegas, Nev.) is an Arcview 3.x extension [Environmental Systems Research Institute (Esri), Redlands, Calif.] developed by the USEPA that computes a number of landscape, riparian, and watershed metrics, and is available at: *http://www.epa.gov/esd/land-sci/attila/* (Ebert and Wade, 2004). Metrics are presented here at the county level and mapped at the watershed level (12-digit Hydrologic Unit Codes).

## Disturbance

Disturbance is a key concept in a landscape analysis approach and in ecology in general. Gas development activities create a number of disturbances across a heterogeneous landscape. In landscape analysis, disturbances are discrete events in space and time that disrupt ecosystem structure and function and change resource availability and the physical environment (White and Pickett, 1985; Turner and others, 2001). When natural or anthropogenic disturbance occurs in natural systems, it generally alters abiotic and biotic conditions that favor the success of different species, such as opportunistic invasive species over predisturbance organisms. Natural gas exploration and development result in spatially explicit patterns of landscape disturbance involving the construction of well pads and impoundments, roads, pipelines, and disposal activities that have structural impacts on the landscape (fig. 2).

Development of multiple sources of natural gas will result in increased traffic from construction, drilling operations (horizontal and vertical), hydraulic fracturing, extraction, transportation, and maintenance activities. The mere presence of humans, construction machinery, infrastructure (for example, well pads and pipelines), roads, and vehicles alone may substantially impact flora and fauna. Increased traffic, especially rapid increases on roads that have historically received little activity, can have detrimental impacts to populations (Gibbs and Shriver, 2005). Forest loss as a result of disturbance, fragmentation, and edge effects has been shown to negatively affect water quality and runoff (Wickham and others, 2008), to alter biosphere-atmosphere dynamics that could contribute to climate change (Bonan, 2008; Hayden, 1998), and to affect even the long-term survival of the forest itself (Gascon and others, 2007). The initial step of landscape analysis is to determine the spatial distribution of disturbance to identify relative hotspots of activity. Disturbance in this report is presented as both graphic files and tables of summary statistics. This knowledge allows greater focus to be placed on specific locations. Figure 5 provides an example of the distribution of natural gas extraction in

Bradford County, Pennsylvania. The figure also shows how that disturbance is placed with respect to the local land cover.

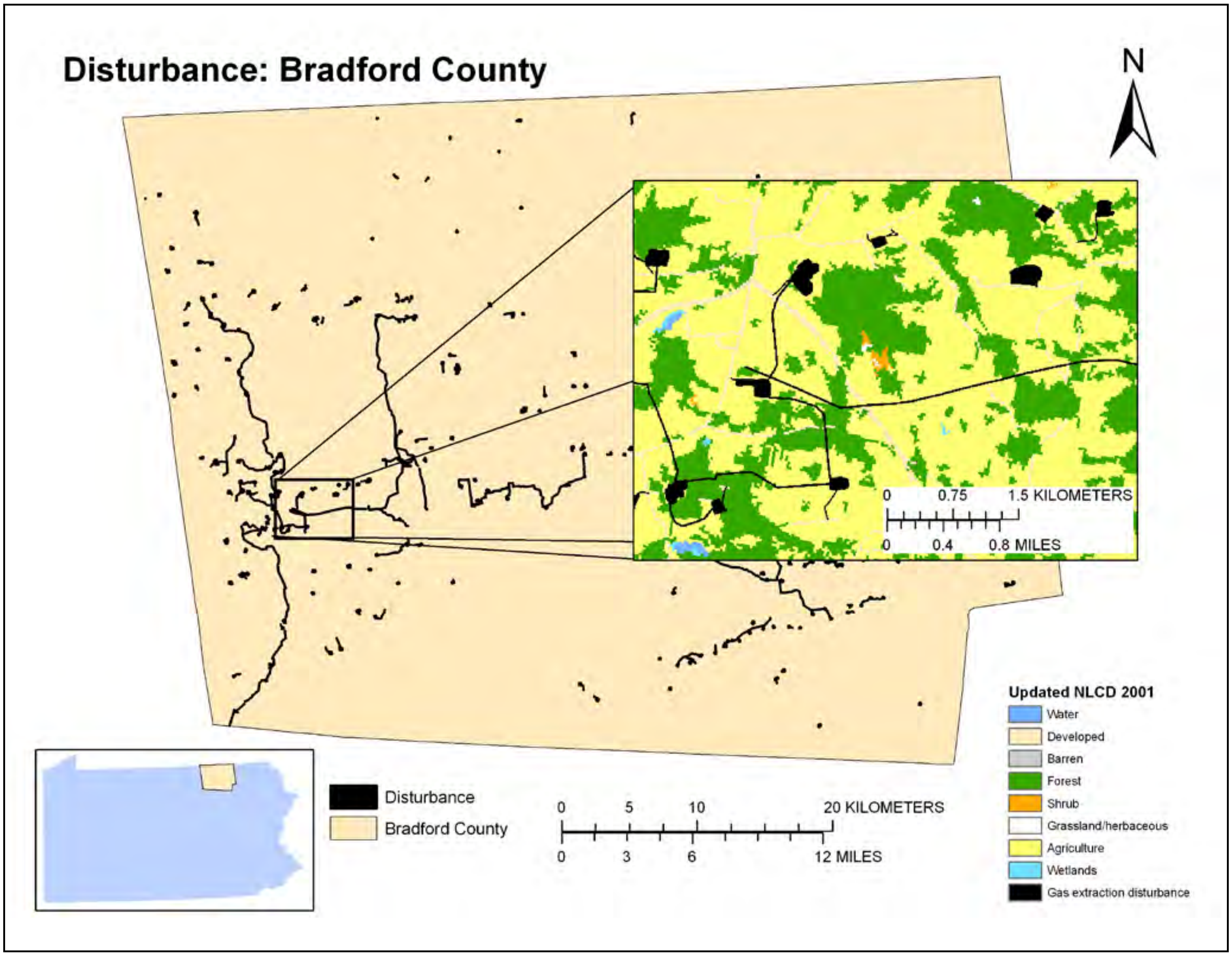

**Figure 5.** The natural gas disturbance footprint of Bradford County, Pennsylvania, embedded within the National Land Cover Dataset (NLCD) 2001. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## Forest Fragmentation

Fragmentation of forest and habitat is a primary concern resulting from current gas development. Habitat fragmentation occurs when large areas of natural landscapes are intersected and subdivided by other, usually anthropogenic, land uses leaving smaller patches to serve as habitat for various species. As human activities increase, natural habitats, such as forests, are divided into smaller and smaller patches that have a decreased ability to support viable populations of individual species. Habitat loss and forest fragmentation can be major threats to biodiversity, although research on this topic has not been conclusive (With and Pavuk, 2011).

Although many human and natural activities result in habitat fragmentation, gas exploration and development activity can be extreme in their effect on the landscape. Numerous secondary roads and pipeline networks crisscross and subdivide habitat structure. Landscape disturbance associated with shale-gas development infrastructure directly alters habitat through loss, fragmentation, and edge effects, which in turn alters the flora and fauna dependent on that habitat. The fragmentation of habitat is expected to amplify the problem of total habitat area reduction for wildlife species, as well as contribute towards habitat degradation. Fragmentation alters the landscape by creating a mosaic of spatially distinct habitats from originally contiguous habitat, resulting in smaller patch size, greater number of patches, and decreased interior to edge ratio (Lehmkuhl and Ruggiero, 1991; Dale and others, 2000). Fragmentation generally results in detrimental impacts to flora and fauna, resulting from increased mortality of individuals moving between patches, lower recolonization rates, and reduced local population sizes (Fahrig and Merriam, 1994). The remaining patches may be too small, isolated, and possibly too influenced by edge effects to maintain viable populations of some species. The rate of landscape change can be more important than the amount or type of change because the temporal dimension of change can affect the probability of recolonization for endemic species, which are typically restricted by their dispersal range and the kinds of landscapes in which they can move (Fahrig and Merriam, 1994).

While general assumptions and hypotheses can be derived from existing scientific literature involving similar stressors, the specific impacts of habitat loss and fragmentation in the Marcellus Shale Play will depend on the needs and attributes of specific species and communities. A recent analysis of Marcellus well permit locations in Pennsylvania found that well pads and associated infrastructure (roads, water impoundments, and pipelines) required nearly 3.6 hectares (9 acres) per well pad with an additional 8.5 hectares (21 acres) of indirect edge effects (Johnson, 2010). This type of extensive and long-term habitat conversion has a greater impact on natural ecosystems than activities such as logging or agriculture, given the great dissimilarity between gas-well pad infrastructure and adjacent natural areas and the low probability that the disturbed land will revert back to a natural state in the near future (high persistence) (Marzluff and Ewing, 2001). Figure 6 shows an example of the concept of the landscape metric of forest fragmentation.

## Interior Forest

Interior forest is a special form of habitat that is preferred by many plant and animal species and is defined as the area of forest at least 100 meters from the forest edge (Harper and others, 2005). Interior forest is an important landscape characteristic because the environmental conditions, such as light, wind, humidity, and exposure to predators, within the interior forest are very different from areas closer to the forest edge. Interior forest habitat is related to the size and distribution of forest patches and is closely tied to the concept of forest or habitat **fragmentation**—the alteration of habitat into smaller, less functional areas. The amount of interior forest can be dramatically affected by linear land use patterns, such as roads and pipelines, which tend to fragment land patches into several smaller patches and destroy available habitat for certain species. Figure 6 shows the general concept of increased fragmentation and reduced interior forest.

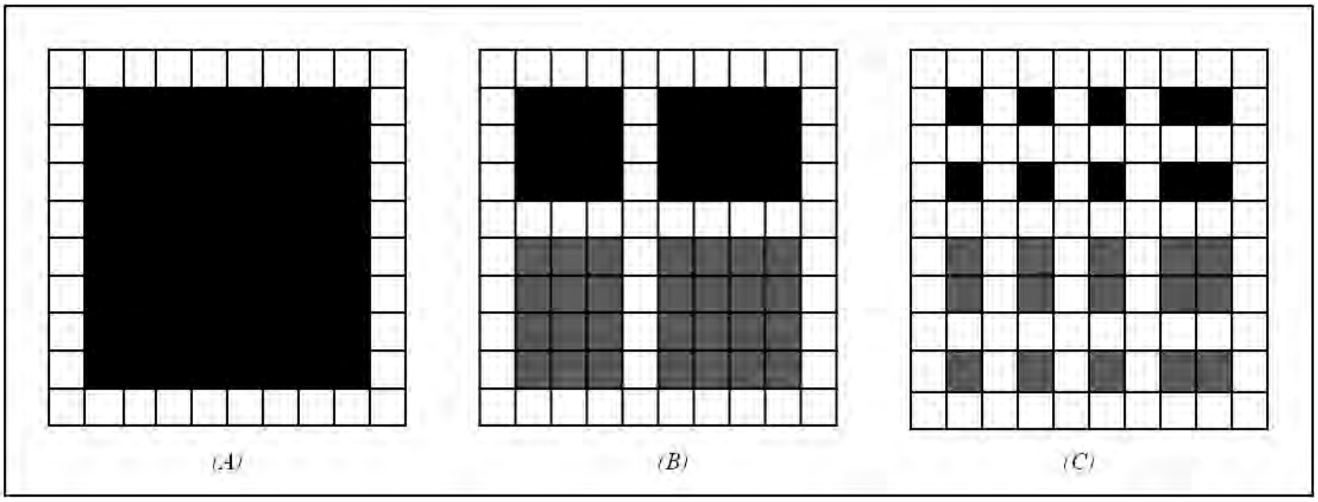

**Figure 6.** Conceptual illustration of interior forest and how this critical habitat is affected by linear disturbance. (*A*) High interior area, (*B*) Moderate interior area, and (*C*) Low interior area (Riitters and others, 1996).

## Forest Edge

Forest edge is simply a linear measure of the amount of edges between forest and other land uses in a given area, and especially between natural and human-dominated landscapes. The influence of the two bordering communities on each other is known as the edge effect. When edges are expanded into natural ecosystems, and the area outside the boundary is a disturbed or unnatural system, the natural ecosystem can be affected for some distance in from the edge (Skole and Tucker, 1993). Edge effects are variable in space and time. The intensity of edge effects diminishes as one moves deeper inside a forest, but edge phenomena can vary greatly within the same habitat fragment or landscape (Laurance and others, 2007). Factors that might promote edge-effect variability include the age of habitat edges, edge aspect, and the combined effects of multiple nearby edges, fragment size, seasonality, and extreme weather events.

Spatial variability of edge effects may result from local factors such as the proximity and number of nearby forest edges. Plots with two or more neighboring edges, such as smaller fragment plots, have greater tree mortality and biomass loss. Edge age also influences edge effects. Over time, forest edge is partially sealed by proliferating vines and second underbrush growth, which will influence the ability of smaller tree seedlings to survive in this environment. Likewise, the matrix of adjoining vegetation plots will have a strong influence on edge effects. Forest edges adjoined by young regrowth forest provide a physical buffer from wind and light. Extreme weather events also affect the temporal variability in edge effects. Abrupt, artificial boundaries of forest fragments are vulnerable to windstorms, snow and ice, and convectional thunderstorms that can weaken and destroy exposed forest edges. Periodic droughts can also have a more pronounced effect on forest edges that are exposed to drier wind conditions and higher rates of evaporation.

## Contagion

Contagion is an indicator that measures the degree of “clumpiness” among the classes of land cover features and is related to patch size and distribution. Contagion expresses the degree to which adjacent pixel pairs can be found in the landscape. Figure 7 shows the general concept of contagion and gives examples of low, medium, and high contagion. Contagion is valuable because it relates an important measure of how landscapes are fragmented by patches. Landscapes of large, less-fragmented patches have a high contagion value and landscapes of numerous small patches have a low contagion value (McGarigal and others, 2002).

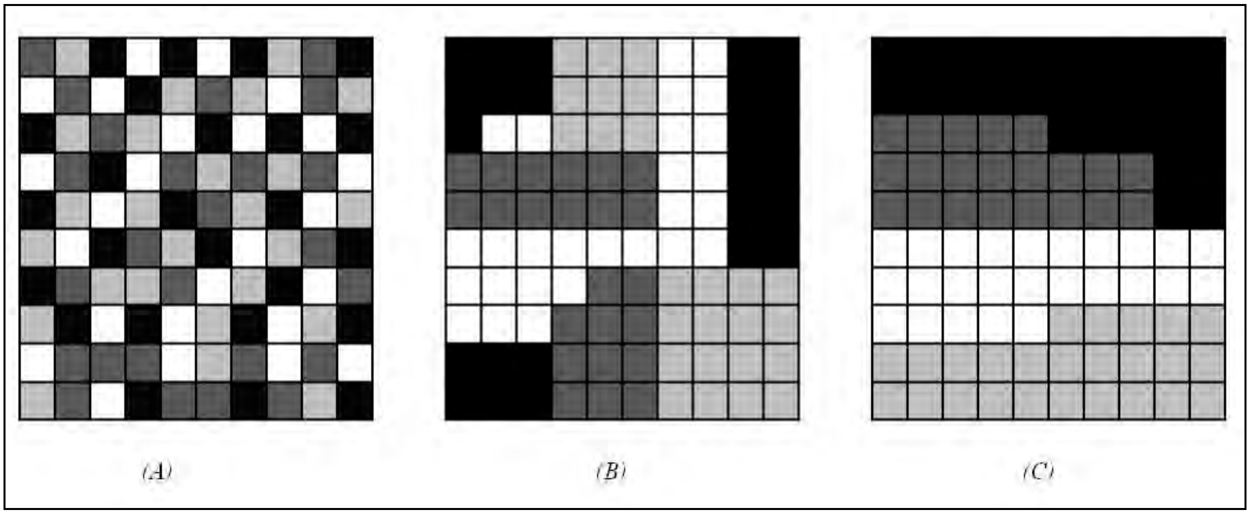

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or “clumped” to one another. (*A*) Low contagion, (*B*) Moderate contagion, and (*C*) High contagion (Riitters and others 1996).

### Fractal Dimension

Fractal dimension describes the complexity of patches or edges within a landscape and is generally related to the level of anthropogenic influence in a landscape. Fractal dimension generally measures the relationship of a patch by a perimeter-to-area proportion. Human land uses tend to have simple, circular, or rectangular shapes of low complexity and, therefore, low fractal dimensions. Natural land covers have irregular edges, complex arrangements and, therefore, higher fractal dimensions. The fractal-dimension index ranges between 1 and 2, with 1 indicating high human influences in the landscape and 2 with natural patterns and low human influence (McGarigal and others, 2002).

### Dominance

Dominance is a measure of the relative abundance of different patch types, typically emphasizing either relative evenness or equity in the distribution. Dominance is high when one land cover type occupies a relatively large area of a given landscape, and is low when land cover types are evenly distributed. Dominance is the complement to evenness, and is sometimes used as an alternative measure of the relative area of one land cover type over others in the landscape.

Although there are many metrics associated with dominance, here we report on a simple landscape metric—the Simpson’s Evenness Index, which is basically a measure of the proportion of the landscape occupied by a patch type divided by the total number of patch types in the landscape (McGarigal and others, 2002).

## Methodology: Mapping and Measuring Disturbance Effects

High-resolution aerial imagery for each of four timeframes—2004, 2005/2006, 2008, and 2010—were brought into a GIS database, along with additional geospatial data on Marcellus and non-Marcellus well permits and locations, administrative boundaries, ecoregions, and geospatial information on the footprint of the Marcellus Shale Play in Pennsylvania. The imagery was examined for distinct signs of disturbance related to oil and gas drilling and development. The observable features were manually digitized as line and polygon features in a GIS format. The polygons and line features were processed and aggregated into a raster mask used to update existing land cover data. Summary statistics for each county were developed and reported. Detailed landscape metrics were calculated and mapped over watersheds (HUC-12 hydrounits) within and intersecting the boundary of each county.

## Data

### Sources

High-resolution aerial imagery from the National Agricultural Imagery Program (NAIP) was downloaded for each timeframe. NAIP imagery is flown to analyze the status of agricultural lands approximately every 2 to 3 years (U.S. Department of Agriculture, Farm Service Agency, 2011). The NAIP imagery consists of readily available, high-resolution data that are suitable for detailed analysis of the landscape. NAIP imagery is available from the U.S. Department of Agriculture Geospatial Data Gateway Web site (U.S. Department of Agriculture, Natural Resources Conservation Service, 2011).

Drilling permits for Marcellus Shale and non-Marcellus Shale natural gas were obtained from the Pennsylvania Department of Environmental Protection Permit and Rig Activity Reports for 2004–2010 (Pennsylvania Department of Environmental Protection, Office of Oil and Gas Management, 2011).

The U.S. Geological Survey (USGS) Watershed Boundary Dataset Hydrologic Unit Code 12-digit (HUC12) for Pennsylvania was downloaded from the USGS National Hydrography Dataset Web site (U.S. Geological Survey, 2011).

The Marcellus Shale Play assessment unit boundaries were downloaded from the USGS Energy Resources Program Data Services Web site (U.S. Geological Survey, 2012).

The 2001 National Land Cover Dataset (NLCD) was acquired for use as the baseline land cover map. The NLCD is a 16-class land cover classification scheme applied consistently across the United States at a 30-meter spatial resolution (Homer and others, 2007). The NLCD may be acquired using the Multi-Resolution Land Characteristics Consortium Web site (U.S. Geological Survey, 2011).

### Collection

These data were brought into a GIS database for spatial analysis. Using the 2004 imagery as a baseline, the imagery was examined for distinct signs of disturbance related to oil and gas drilling and development. These mapped disturbance features include:

- Well Pads - Cleared areas related to existing permits or displaying the characteristics of a shale or coalbed gas extraction site.
- Roads - Vehicular transportation corridors constructed specifically for shale or coalbed gas development.
- Pipelines - New gas pipelines constructed in conjunction with one or more well pads.
- Impoundments - Manmade depressions designed to hold liquid and in support of oil and gas drilling operations.
- Other - Support areas or activities such as processing plants, storage tanks, and staging areas.

The collection of gas extraction infrastructure was a manual process of visually examining high-resolution imagery for each county over four dates to identify and digitize (collect) changes in the land cover resulting from the development of gas extraction infrastructure. Specifically, we examined NAIP

1-meter data for the years 2004, 2005/2006, 2008, and 2010, identifying landscape changes that occurred after 2004. We selected those changes that appeared to be gas extraction related or were in proximity to other gas extraction infrastructure and digitized the maximum extent of landscape disturbance over the years of interest. We focused on features attributable to the construction, use, and maintenance of gas extraction drill sites, processing plants, and compressor stations, as well as the center lines for new roads accessing such sites, plants, and stations, and the center lines for new pipelines used to transport the extracted gas. Figure 8 shows examples of digitized natural gas extraction features. These data were collected within shapefiles per county, using ArcGIS 10.0 (Esri, Redlands, Calif.). One shapefile was generated for sites (polygons), one was generated for roads, and one was generated for pipelines (lines). Roads and pipelines were generally buffered to 8 and 12 meters, respectively, for overall area assessments. All sites were initially classified as gas extraction related or points of interest. Points of interest were unlikely to be related to drilling, but were of potential future interest and excluded from further processing. All data collected were reviewed by another team member for concurrence and consistency.

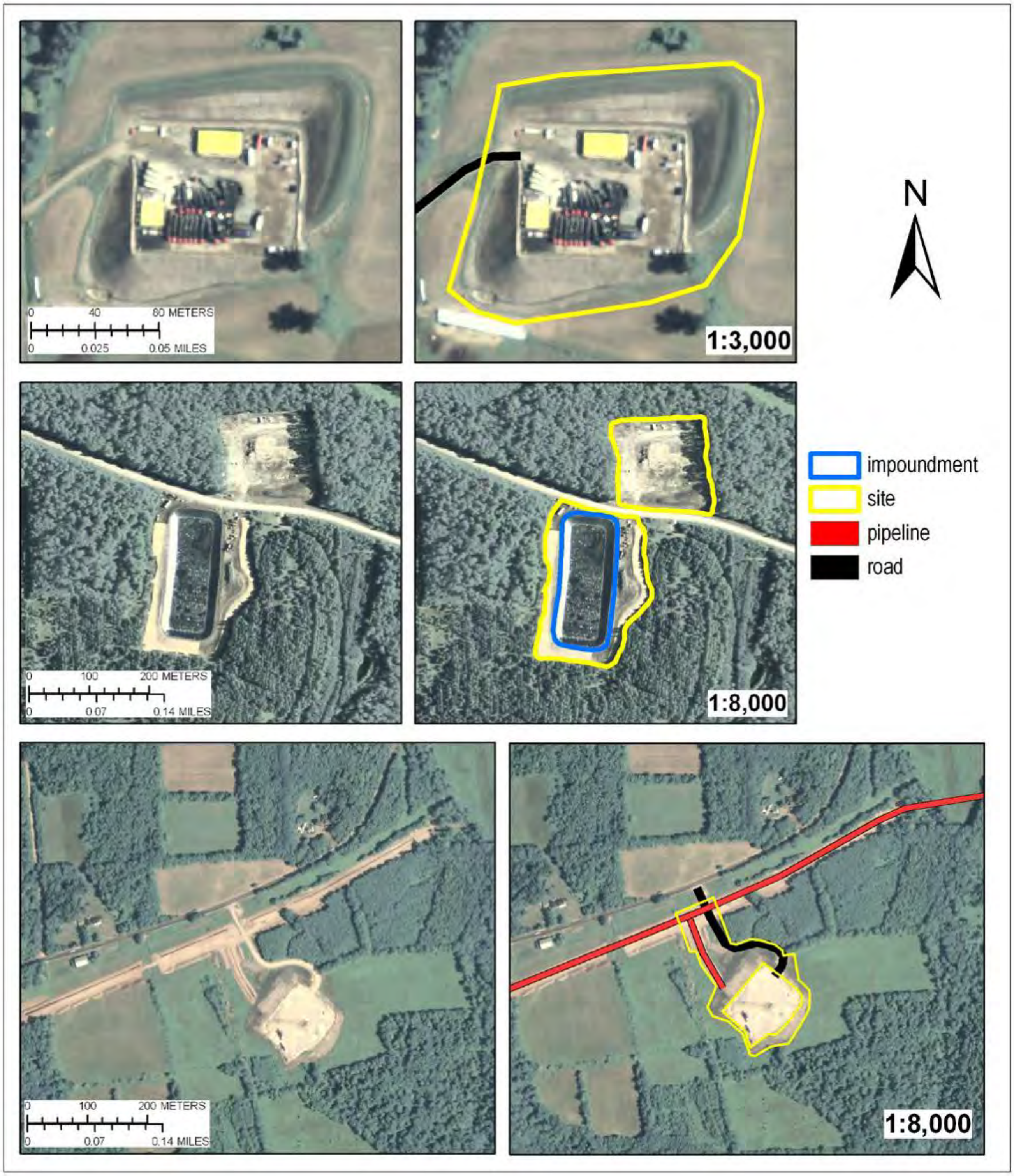

**Figure 8.** Examples of spatially explicit features of disturbance that are being extracted from aerial photos into a geographic information systems (GIS) format.

## Land Cover Update

Using the collected and reviewed data, the polygons and line features were processed and aggregated into a raster format used as a mask to update existing land cover data from NLCD 2001. Figure 9 shows the processing flow to accomplish this task consistently across all counties.

Each feature within the shapefiles was then processed to determine its permit status and area. Each county's shapefiles were then merged and internal boundaries dissolved resulting in a disturbance footprint for that county. The disturbance footprint was then rasterized and used to conditionally select the pixels in the 2001 NLCD to reclassify as a new class: gas extraction disturbance. To consistently perform this processing, a set of models was developed using the ArcGIS Modelbuilder (Esri, Redlands, Calif.).

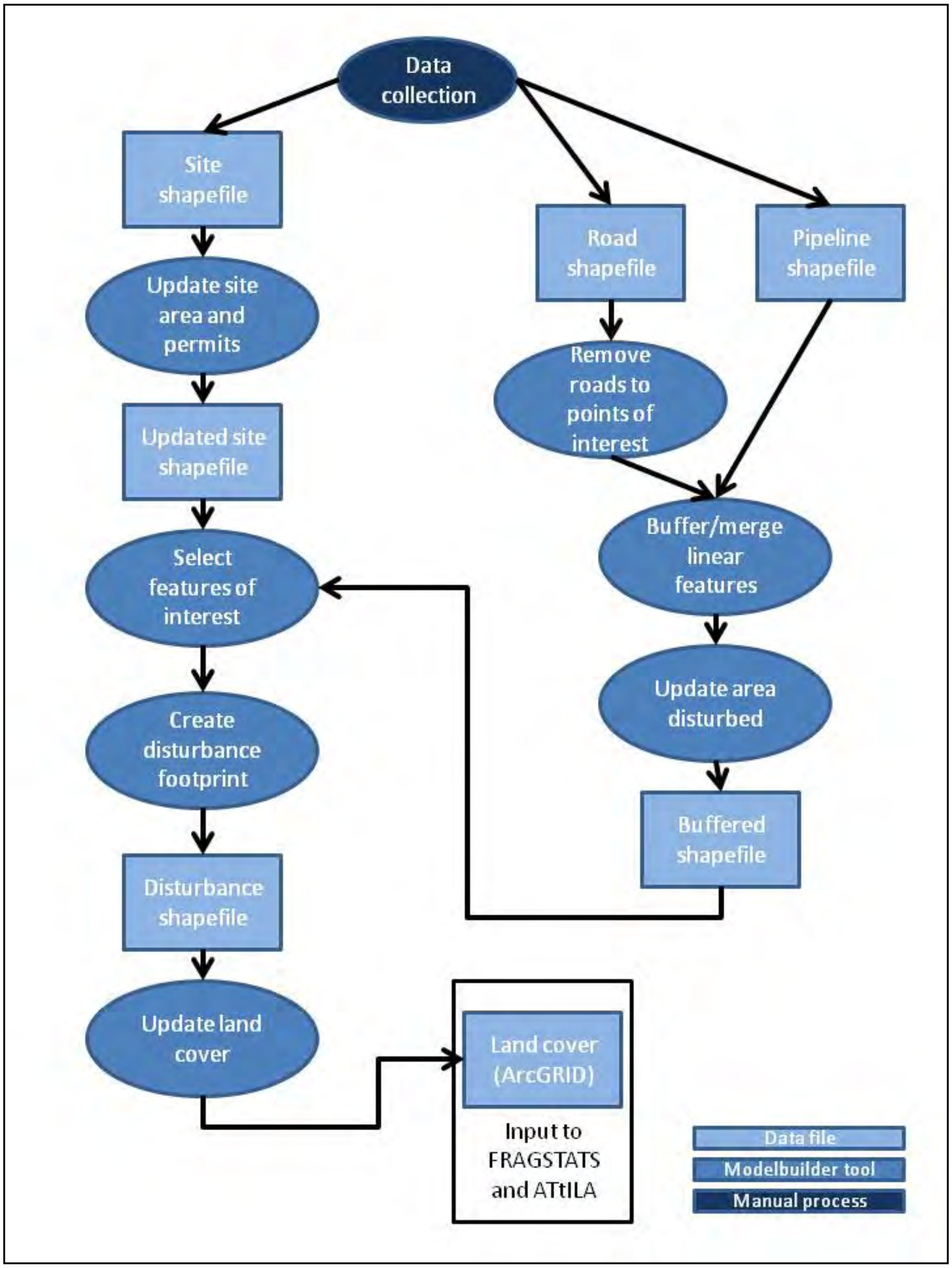

**Figure 9.** Workflow diagram for creating an updated land cover map.

## Calculation of Landscape Metrics

Landscape-wide and land cover class fragmentation statistics for each county were developed and reported using FRAGSTATS, while land cover class-detailed statistics, forest fragmentation statistics, including patch metrics and forest condition (interior, edge, and so forth) metrics were calculated over smaller watersheds (HUC12) intersecting with the county using ATtILA. The collected statistics were then summarized, charted, and mapped for further analysis.

In addition to the summary of features noted above, a series of landscape metrics was calculated for each county based on the change related to gas development activities between 2004 and 2010. To do this, the metrics were calculated from the 2001 NLCD dataset (Homer and others, 2007). Following that calculation, the 2004–2010 cumulative spatial pattern of disturbance was digitally embedded into the 2001 NLCD dataset and the metrics were recalculated for each county.

## Results: Summary Statistics and Graphics

This section presents a summary of landscape alterations from natural gas resource development, along with the ensuing change in land cover and landscape metrics for each county using metrics suggested by O'Neill and others (1997). These metrics are then calculated and presented based on the sources of that disturbance: Marcellus sites and roads, non-Marcellus sites and roads, and other infrastructure, which includes nonpermitted sites, processing facilities and their associated roads, and pipelines and their associated roads. Nonpermitted sites are defined as disturbed areas that appear to be Marcellus or non-Marcellus gas extraction sites that do not have a permit within 250 m. These data are presented in tabular form with some graphic presentations provided where appropriate. Examples of the spatial distribution of selected landscape metrics are shown at the watershed level for each county. GIS data of all disturbance features are available upon request.

### Disturbed Area

Documenting the spatially explicit patterns of disturbance was one of the primary goals of this research, and this section describes the extent of disturbed land cover for Bradford and Washington Counties in Pennsylvania. The spatial distribution of disturbance influences the impacts of that disturbance. Figure 10 shows the distribution of disturbance within Bradford and Washington Counties. In Washington County, the disturbance occurs in two general clusters: the northwest, which is mostly Marcellus Shale development, and the southeast, which is mostly non-Marcellus Shale development. On the other hand, Bradford County shows most of the disturbance at the western portion of the county, with some minor disturbance in the east. The detailed insets show the disturbance footprints in the context of the surrounding land cover.

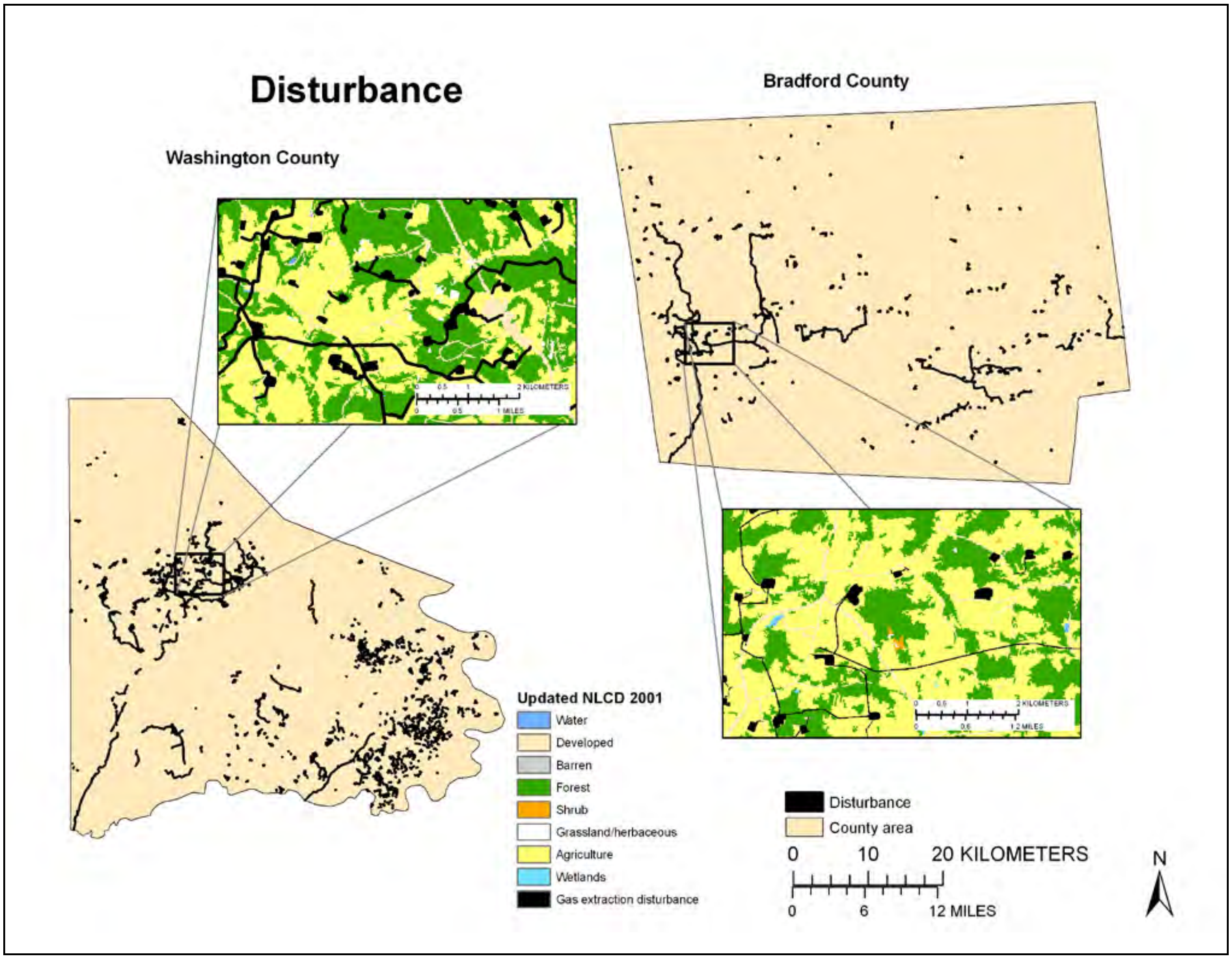

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Bradford and Washington Counties, Pennsylvania. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

Table 1 lists the disturbance area attributable to all sites and impoundments and their associated roads and pipelines. The disturbance area is presented first as a total disturbance for all gas extraction infrastructure, including all sites, roads, and pipelines. Total disturbance is broken into two sections: disturbance for all sites and their associated roads and disturbance for pipelines. The disturbance area for all sites and roads is further broken into disturbance for Marcellus Shale sites and roads, non-Marcellus Shale sites and roads, sites with permits for both Marcellus and non-Marcellus drilling, and sites lacking an identifiable permit (for example, processing facilities or incomplete permit data). Additionally, disturbance area associated with impoundments is presented for those impoundments greater than 0.40 hectares and for those that are less than 0.40 hectares. Because land disturbance or access roads may be associated with multiple infrastructure (for example, pipelines may cross areas also disturbed for drill sites), the values for disturbed areas and road miles within break-out categories such as “MS sites and roads” do not sum up to the higher level category, in this instance “All sites and roads.” The results indicate the following:

- While Bradford County is larger (~300,000 hectares) than Washington County (~223,000 hectares), Bradford County has 210 Marcellus and 19 non-Marcellus sites compared to 170 Marcellus and 501 non-Marcellus sites in Washington County.
- The mean hectares of disturbance per site are smaller (1.3 hectares) in Washington County than in Bradford County (2.0 hectares) because of the greater number of smaller non-Marcellus sites.
- The mean disturbed hectares for Marcellus sites is almost identical for both counties (3.0 hectares for Bradford and 2.9 hectares for Washington), whereas the mean disturbed hectares per non-Marcellus sites is almost three times larger in Bradford County than in Washington County. A visual examination of the Bradford non-Marcellus sites reveals several large sites that include impoundments or multiple wells.
- Washington County has almost four times the number of sites that include processing and transportation facilities and nonpermitted sites than Bradford County, and these sites have a much larger mean size (18.5 hectares). This difference may be attributed to the processing facilities for "wet gas," multiple hydrocarbons that are commonly extracted in this area.
- Both counties have about the same number of sites with both Marcellus and non-Marcellus permits. The disturbance associated with dual sites is included in the disturbance measures for both Marcellus and non-Marcellus sites.
- Bradford County has almost 20 times the number of large impoundments (greater than 0.40 hectares) and these impoundments are almost twice the mean size of those in Washington County, implying a difference in water access, storage, and usage.

**Table 1.** Amount of landscape disturbance for natural gas extraction development and infrastructure based on disturbance type. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

| Land cover update | Count | Site only hectares | Footprint disturbed hectares | Road kilometers | Pipeline kilometers | Hectares per site | Disturbed hectares per site | Road kilometers per site |
|---|---|---|---|---|---|---|---|---|
| Bradford County (300,991.7 hectares) | | | | | | | | |
| All infrastructure | 642 | 1,300.3 | 1,506.3 | 74.82 | 178.4 | 2.0 | 2.3 | 0.2 |
| All sites and roads | 262 | 742.4 | | 73.7 | | | | |
| MS sites and roads | 210 | 616.7 | 865.8 | 66.1 | | 3.0 | 4.1 | 0.3 |
| non-MS sites and roads | 19 | 49.2 | 58.4 | 5.8 | | 2.5 | 3.1 | 0.3 |
| Other infrastructure/ unpermitted sites and roads | 44 | 116.5 | 143.0 | 5.5 | | 2.6 | 3.2 | 0.2 |
| Dual sites | 11 | 39.9 | | | | | | |
| Pipelines | 97 | 432.7 | 450.3 | 77.4 | 178.4 | | | |
| Impoundments (>0.40 ha) | 561 | 1,203.7 | | | | 2.1 | | |
| Impoundments (<0.40 ha) | 121 | 22.7 | | | | 0.2 | | |
| Washington County (223,469.0 hectares) | | | | | | | | |
| All infrastructure | 949 | 1,196.86 | 1,847.17 | 277.2 | 216.0887 | 1.3 | 1.9 | 0.3 |
| All sites and roads | 832 | 1,057.48 | | 272.1 | | | | |
| MS sites and roads | 170 | 496.45 | 728.54 | 88.0 | | 2.9 | 4.3 | 0.5 |
| non-MS sites and roads | 501 | 390.01 | 1,019.60 | 162.0 | | 0.8 | 2.0 | 0.3 |
| Other infrastructure/ unpermitted sites and roads | 173 | 214.37 | 385.48 | 73.4 | | 1.3 | 2.2 | 0.5 |
| Dual sites | 12 | 43.4 | | | | | | |
| Pipelines | 117 | 523.4 | 598.2 | 63.4 | 216.1 | | | |
| Impoundments (>0.40 ha) | 29 | 34.0 | | | | 1.2 | | |
| Impoundments (<0.40 ha) | 130 | 11.9 | | | | 0.1 | | |

Land cover change is the initial impact of disturbance and has long-term effects on ecological goods and services. Table 2 lists the percent land cover by county for 2001 and percent land cover and change for the updated 2010 landscape. The land cover change for the updated landscape is further broken into the values attributable to Marcellus sites; non-Marcellus sites; other infrastructure including nonpermitted sites; and pipelines, each with their associated roads. Given that the natural land cover of Pennsylvania is forest (Kuchler, 1964), the 2001 land cover provides a measure of the impacts prior to most natural gas resource development; the changes between 2004 and 2010 have only increased these impacts. Of particular interest are the forest cover and its relation to the critical value 59.28 percent from percolation theory (Gardner and others, 1987; O'Neill and others, 1997). Below this value, the forest structure rapidly breaks down into isolated patches, thereby changing forest resilience and habitat corridors. The results indicate the following:

- In both Bradford and Washington Counties, the primary land covers are forest (56 percent for each), agriculture (35 percent and 27 percent, respectively), and developed (5 percent and 14 percent, respectively). Natural gas resource development had the greatest impact on forest and agricultural land cover.

- Both counties had less than 59.28 percent forest in 2001 and forest has been further impacted by natural gas resource development. Percent forest declined by 0.12 percent in Bradford County and by 0.42 percent in Washington County.

**Table 2.** Percent land cover presented in descending order for each county. Change in percent forest is shown in bold. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

| Land cover | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bradford County | | | | | | | | | | | |
| Forest | 56.12 | 56.01 | -0.12 | 56.06 | -0.06 | 56.12 | -0.01 | 56.11 | -0.01 | 56.07 | -0.05 |
| Agriculture | 35.47 | 35.20 | -0.27 | 35.31 | -0.16 | 35.46 | -0.01 | 35.44 | -0.03 | 35.38 | -0.09 |
| Developed | 4.96 | 4.95 | -0.01 | 4.96 | 0.00 | 4.96 | 0.00 | 4.96 | 0.00 | 4.96 | -0.01 |
| Grassland - herbaceous | 0.16 | 0.16 | 0.00 | 0.16 | 0.00 | 0.16 | 0.00 | 0.16 | 0.00 | 0.16 | 0.00 |
| Water | 0.96 | 0.96 | 0.00 | 0.96 | 0.00 | 0.96 | 0.00 | 0.96 | 0.00 | 0.96 | 0.00 |
| Barren | 0.11 | 0.11 | 0.00 | 0.11 | 0.00 | 0.11 | 0.00 | 0.11 | 0.00 | 0.11 | 0.00 |
| Wetlands | 0.75 | 0.75 | 0.00 | 0.75 | 0.00 | 0.75 | 0.00 | 0.75 | 0.00 | 0.75 | 0.00 |
| Scrub - shrub | 1.46 | 1.45 | -0.01 | 1.45 | -0.01 | 1.46 | 0.00 | 1.46 | 0.00 | 1.46 | 0.00 |
| Gas extraction disturbance | | 0.41 | 0.41 | 0.23 | 0.23 | 0.02 | 0.02 | 0.04 | 0.04 | 0.15 | 0.15 |
| Washington County | | | | | | | | | | | |
| Forest | 56.6 | 56.18 | -0.42 | 56.5 | -0.1 | 56.46 | -0.14 | 56.53 | -0.07 | 56.45 | -0.16 |
| Agriculture | 27.35 | 26.99 | -0.37 | 27.2 | -0.15 | 27.25 | -0.11 | 27.29 | -0.06 | 27.26 | -0.09 |
| Developed | 13.64 | 13.61 | -0.03 | 13.64 | 0 | 13.63 | -0.01 | 13.64 | -0.01 | 13.63 | -0.02 |
| Grassland - herbaceous | 1.53 | 1.51 | -0.01 | 1.52 | 0 | 1.52 | 0 | 1.52 | 0 | 1.52 | 0 |
| Water | 0.62 | 0.62 | 0 | 0.62 | 0 | 0.62 | 0 | 0.62 | 0 | 0.62 | 0 |
| Barren | 0.2 | 0.2 | 0 | 0.2 | 0 | 0.2 | 0 | 0.2 | 0 | 0.2 | 0 |
| Wetlands | 0.04 | 0.04 | 0 | 0.04 | 0 | 0.04 | 0 | 0.04 | 0 | 0.04 | 0 |
| Scrub - shrub | 0.01 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0 | 0.01 | 0 |
| Gas extraction disturbance | | 0.83 | 0.83 | 0.27 | 0.27 | 0.26 | 0.26 | 0.14 | 0.14 | 0.27 | 0.27 |

## Land Cover Metrics of Interest

There are numerous landscape metrics, many of which are redundant. Table 3 lists the total area, number of patches, total edge, mean fractal index, contagion, and dominance metrics for the 2001 county landscape and the metrics and change for the updated 2010 landscape. The metrics and change for the updated landscape are further broken into the values attributable to Marcellus sites; non-Marcellus sites; other infrastructure including nonpermitted sites; and pipelines, each with their associated roads. These metrics were chosen for their overall indication of human impacts on the landscape and environmental quality (O'Neill and others, 1997). Increase in edge, especially between dissimilar land covers, indicates declining resilience of the natural land cover and movement of species, while the decrease in the mean fractal index ($1 \leq x \leq 2$) indicates an increase in human use. Evenness ($0 \leq x \leq 1$, where 0 indicates one land cover and 1 indicates even distribution across land cover classes) indicates the relative heterogeneity of the landscape and is the inverse of the dominance measure (McGarigal and others, 2002) recommended by O'Neill and others (1997). Contagion ($0 < x \leq 100$, disaggregated to aggregated) is an indicator that measures the degree of "clumpiness" among the classes of land cover features. The results indicate the following:

- Total edge increased by 611.9 kilometers and 1,160.9 kilometers for Bradford and Washington Counties, respectively, with the largest amount attributable to pipeline construction.
- Fractal index is low for both, indicating a high level of human presence in these counties, and decreases with natural gas resource development. Bradford County shows a decrease of 0.0013, most of which is attributable to pipeline construction. Washington County shows a decrease of 0.0052, of which half is attributable to pipeline construction.
- Contagion shows a moderate level of clumped land cover. Bradford County has a slightly higher level of contagion than Washington County. The influence of infrastructure type (all, Marcellus, non-Marcellus, other, and pipelines) was similar for Bradford County, but more variable for Washington County. The greatest influence (an increase of 1.422) on contagion in Washington County was from other infrastructure; the remaining infrastructure types all had similar effects. This effect may be associated with the construction of the large processing facility in Houston, Pa.
- Evenness also shows a moderate level of heterogeneity for both counties with no one land cover dominating. Evenness has similar values for each infrastructure type. Given that the expected land cover is all forest and has an evenness value approaching 0, this value indicates a substantially disturbed landscape.

**Table 3.** Landscape metrics. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

[Note: Categories are not mutually exclusive]

| Metric | Original land cover | Updated with all infrastructure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines and roads | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bradford County | | | | | | | | | | | |
| Total area (hectares) | 300,991.7 | 300,991.7 | 0 | 300,991.7 | 0 | 300,991.7 | 0 | 300,991.7 | 0 | 300,991.6 | 0 |
| Total edge (km) | 26,712.4 | 27,324.3 | 611.9 | 26,948.5 | 236.1 | 26,732.7 | 20.3 | 26,744.3 | 31.9 | 27,124.4 | 412 |
| Mean fractal index | 1.1068 | 1.1055 | -0.0013 | 1.1061 | -0.0007 | 1.1067 | -1E-04 | 1.1067 | -0.0001 | 1.1057 | -0.0011 |
| Contagion | 70.7925 | 71.7554 | 0.9629 | 71.9771 | 1.1846 | 72.315 | 1.5225 | 72.2781 | 1.4856 | 72.0422 | 1.2497 |
| Evenness | 0.6359 | 0.6295 | -0.0064 | 0.628 | -0.0079 | 0.6261 | -0.0098 | 0.6263 | -0.0096 | 0.6273 | -0.0086 |
| Washington County | | | | | | | | | | | |
| Total area (hectares) | 223,469.0 | 223,469.0 | 0 | 223,469.0 | 0 | 223,469.0 | 0 | 223,469.0 | 0 | 223,469.0 | 0 |
| Total edge (km) | 24,270.1 | 25,431.1 | 1,160.9 | 24,515.9 | 245.7 | 24,704.1 | 433.9 | 24,466.8 | 196.6 | 24,833.9 | 563.8 |
| Mean fractal index | 1.1301 | 1.1249 | -0.0052 | 1.1286 | -0.0015 | 1.1282 | -0.0019 | 1.1292 | -0.0009 | 1.1273 | -0.0028 |
| Contagion | 68.3976 | 68.8579 | 0.4603 | 69.6523 | 1.2547 | 69.5983 | 1.2007 | 69.8187 | 1.4211 | 69.5614 | 1.1638 |
| Evenness | 0.6696 | 0.6667 | -0.0029 | 0.6669 | -0.0027 | 0.6617 | -0.0079 | 0.6661 | -0.0035 | 0.6668 | -0.0028 |

## Forest Fragmentation

Disturbance in the landscape will affect forests by fragmentation, which is the process of dividing large land cover (for example, forest) into smaller segments called patches. A patch is defined as adjacent (forest) pixels, including diagonals. A landscape with many small patches is representative of a highly fragmented landscape. Fragmented forests provide habitat for edge species, but are poor for interior species, and are unlikely to provide migration corridors.

Fragmentation may be evaluated by change in the number of patches, and change in the mean and (or) median patch size. Table 4 compares the changing forest patch metrics for the 2001 land cover, the updated 2010 land cover, and subsets of the updated 2010 land cover based on Marcellus infrastructure, non-Marcellus infrastructure, other infrastructure, and pipelines. The results indicate the following:

- Forests became more fragmented due to natural gas resource development. Both Bradford and Washington Counties contained more, but smaller forest patches in 2010 than in 2001.
- Bradford County forest patches increased by 306 patches; most (~235 patches) are attributable to pipeline construction. These patches initially averaged over 40 hectares, but that average was reduced by almost 3 hectares in 2010.
- Washington County forest patches increased by almost 1,000 patches; most (~505 patches) are attributable to pipeline construction. These patches initially averaged about 35 hectares and were reduced by 7.5 hectares to a mean of about 27 hectares. Non-Marcellus sites and pipelines had the greatest effect on these values.
- Pipeline construction was the source of most of the increase in forest patch number.

**Table 4.** Forest fragmentation metrics. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

[Note: Categories are not mutually exclusive]

| Distribution statistics | Original land cover | Updated with all infra-structure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infrastructure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bradford County | | | | | | | | | | | |
| Number of patches | 4,188.00 | 4,494.00 | 306.00 | 4,263.00 | 75.00 | 4,198.00 | 10.00 | 4,194.00 | 6.00 | 4,423.00 | 235.00 |
| Forest patch area mean (hectares) | 40.33 | 37.51 | -2.82 | 39.58 | -0.75 | 40.23 | -0.10 | 40.27 | -0.06 | 38.16 | -2.18 |
| Forest patch area median (hectares) | 0.81 | 0.74 | 0.74 | 0.80 | 0.80 | 0.81 | 0.81 | 0.81 | 0.81 | 0.80 | 0.80 |
| Washington County | | | | | | | | | | | |
| Number of patches | 3,660 | 4,644 | 984 | 3,809 | 149 | 4,043 | 383 | 3,798 | 138 | 4,165 | 505 |
| Forest patch area mean (hectares) | 34.56 | 27.04 | -7.52 | 33.15 | -1.41 | 31.21 | -3.35 | 33.26 | -1.30 | 30.29 | -4.27 |
| Forest patch area median (hectares) | 0.73 | 0.62 | -0.11 | 0.72 | -0.01 | 0.65 | -0.08 | 0.72 | -0.01 | 0.71 | -0.02 |

Figure 11 illustrates the spatial distribution of the change in the number of forest patches by watershed. Note the relation between disturbance and the change in the number of forest patches. The increase of over 50 forest patches in some watersheds indicates an increasingly fragmented landscape with habitat implications for many species.

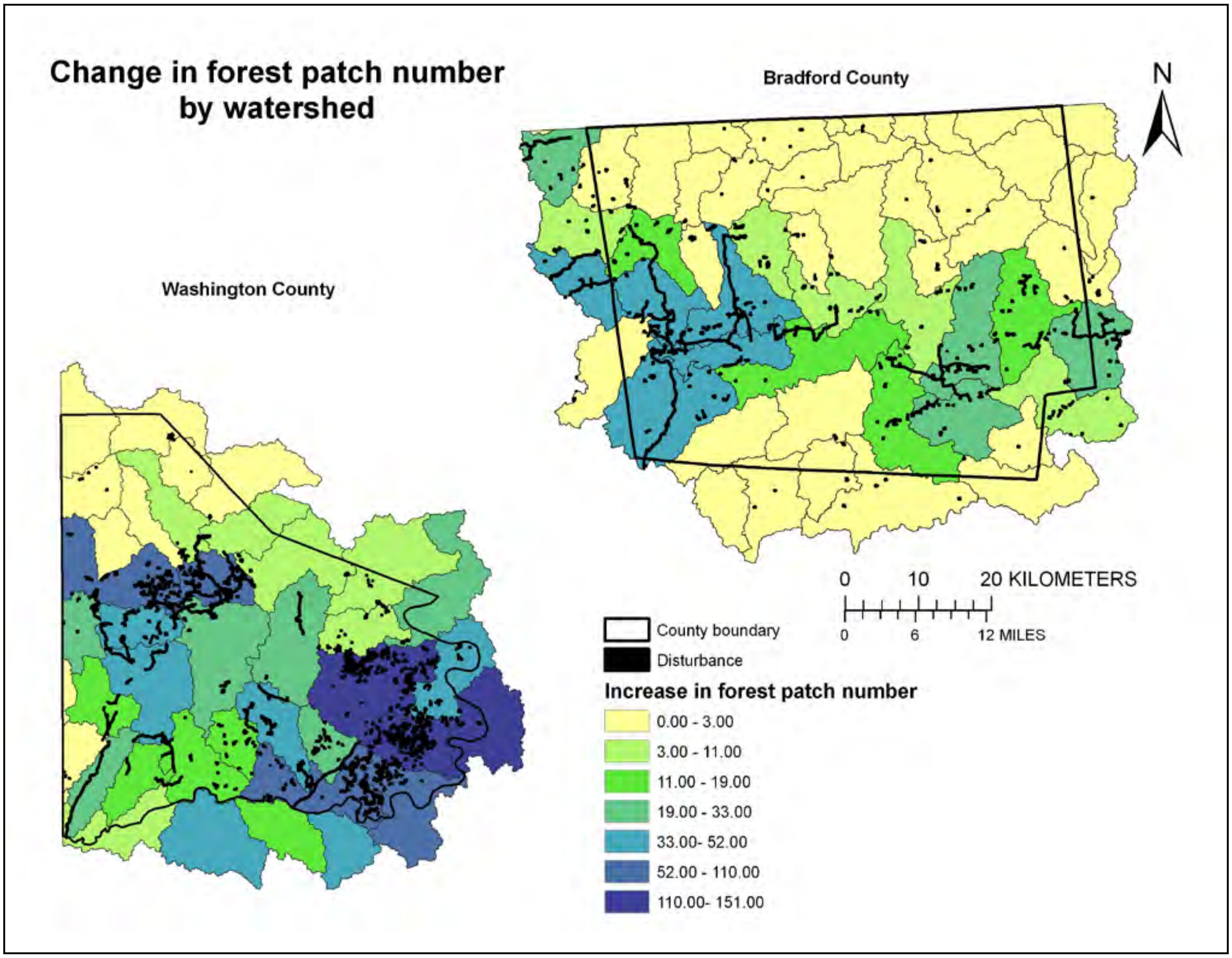

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing increasing fragmentation in Bradford and Washington Counties, Pennsylvania. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## Interior and Edge Forest

Forest condition (interior and edge) is another way to evaluate the state of the forest. In particular, interior forest is subject to more rapid decline than other segments of the forest. Table 5 shows the change in interior forest and edge forest based on natural gas resource development and the types of natural gas extraction infrastructure. Figures 12 and 13, respectively, illustrate the spatial distribution by watershed of change in percent interior forest and the spatial distribution of change in percent edge forest. The results indicate the following:

- Bradford County lost 0.12 percent forest, which contributed to a 0.32-percent loss of interior forest and a gain of 0.11 percent in edge forest.

- Washington County lost 0.42 percent forest, which contributed to a 0.96-percent loss of interior forest and a gain of 0.38 percent in edge forest.
- For both counties, pipeline construction was the major contributor to forest loss, although in Washington County, non-Marcellus sites were a close runner-up.
- A tentative pattern appears in that the interior forest loss is approximately twice that of the overall forest loss, and the gain in edge forest approximates that overall forest loss.

**Table 5.** Change in percent of interior forest and percent edge forest. MS and non-MS sites refer to Marcellus Shale and non-Marcellus Shale sites, respectively.

[Note: Categories are not mutually exclusive]

| Distribution statistics | Original land cover | Updated with all infra-structure | Change | Updated with MS sites and roads | Change | Updated with non-MS sites and roads | Change | Updated with other infra-structure | Change | Updated with pipelines | Change |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bradford County** | | | | | | | | | | | |
| Number of patches | 4,188.00 | 4,494.00 | 306.00 | 4263.00 | 75.00 | 4,198.00 | 10.00 | 4194.00 | 6.00 | 4,423.00 | 235.00 |
| Percent forest | 56.67 | 56.65 | -0.02 | 56.60 | -0.07 | 56.66 | -0.01 | 56.66 | -0.01 | 56.61 | -0.06 |
| Percent interior forest | 38.32 | 38.00 | -0.32 | 38.22 | -0.10 | 38.31 | -0.01 | 38.31 | -0.01 | 38.17 | -0.15 |
| Percent edge forest | 13.21 | 13.32 | 0.11 | 13.24 | 0.03 | 13.21 | 0.00 | 13.22 | 0.01 | 13.28 | 0.07 |
| **Washington County** | | | | | | | | | | | |
| Number of patches | 3,660.00 | 4,644.00 | 984.00 | 3,809.00 | 149.00 | 4,043.00 | 383.00 | 3,798.00 | 138.00 | 4,165.00 | 505.00 |
| Percent forest | 56.96 | 56.54 | -0.42 | 56.85 | -0.11 | 56.81 | -0.15 | 56.89 | -0.07 | 56.80 | -0.16 |
| Percent interior forest | 31.95 | 30.99 | -0.96 | 31.76 | -0.19 | 31.59 | -0.36 | 31.80 | -0.15 | 31.49 | -0.46 |
| Percent edge forest | 18.22 | 18.60 | 0.38 | 18.28 | 0.06 | 18.36 | 0.14 | 18.27 | 0.05 | 18.45 | 0.23 |

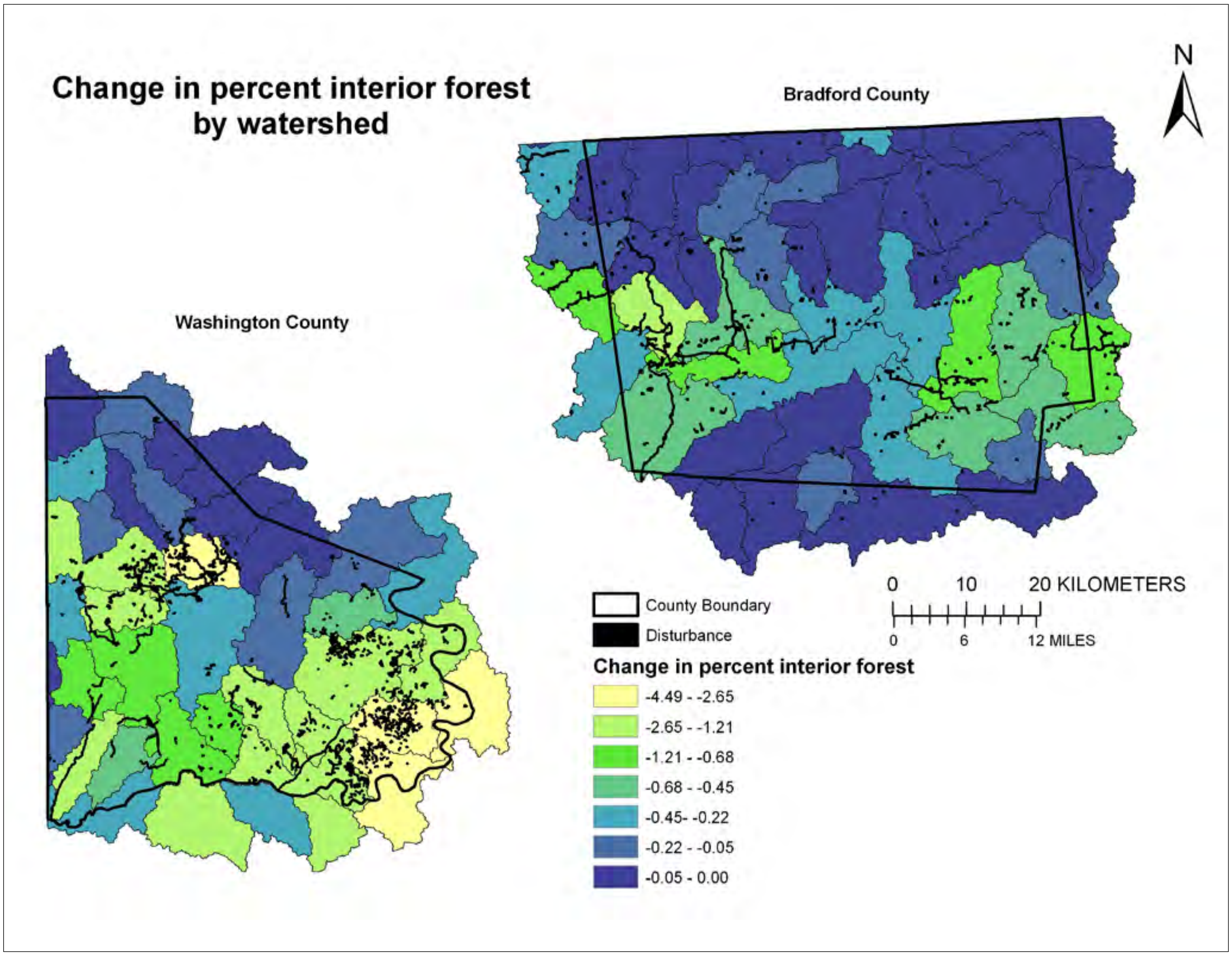

**Figure 12.** Change in percent interior forest by watershed in Bradford and Washington Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## Conclusion

The results presented here show how natural gas extraction in Pennsylvania is affecting the landscape configuration. Agricultural and forested areas are being converted to natural gas extraction disturbance. The disturbance and effects of both Marcellus and non-Marcellus development are clearly different over both counties in that Bradford County has very little non-Marcellus development, but it is important to note that the combined effect of both activities is substantial.

The fractal dimension, contagion, and dominance were reported based on O'Neill and others' recommendations (1997); however, they do not appear to be important in these counties. They may be of greater importance for other counties and are reported here for consistency.

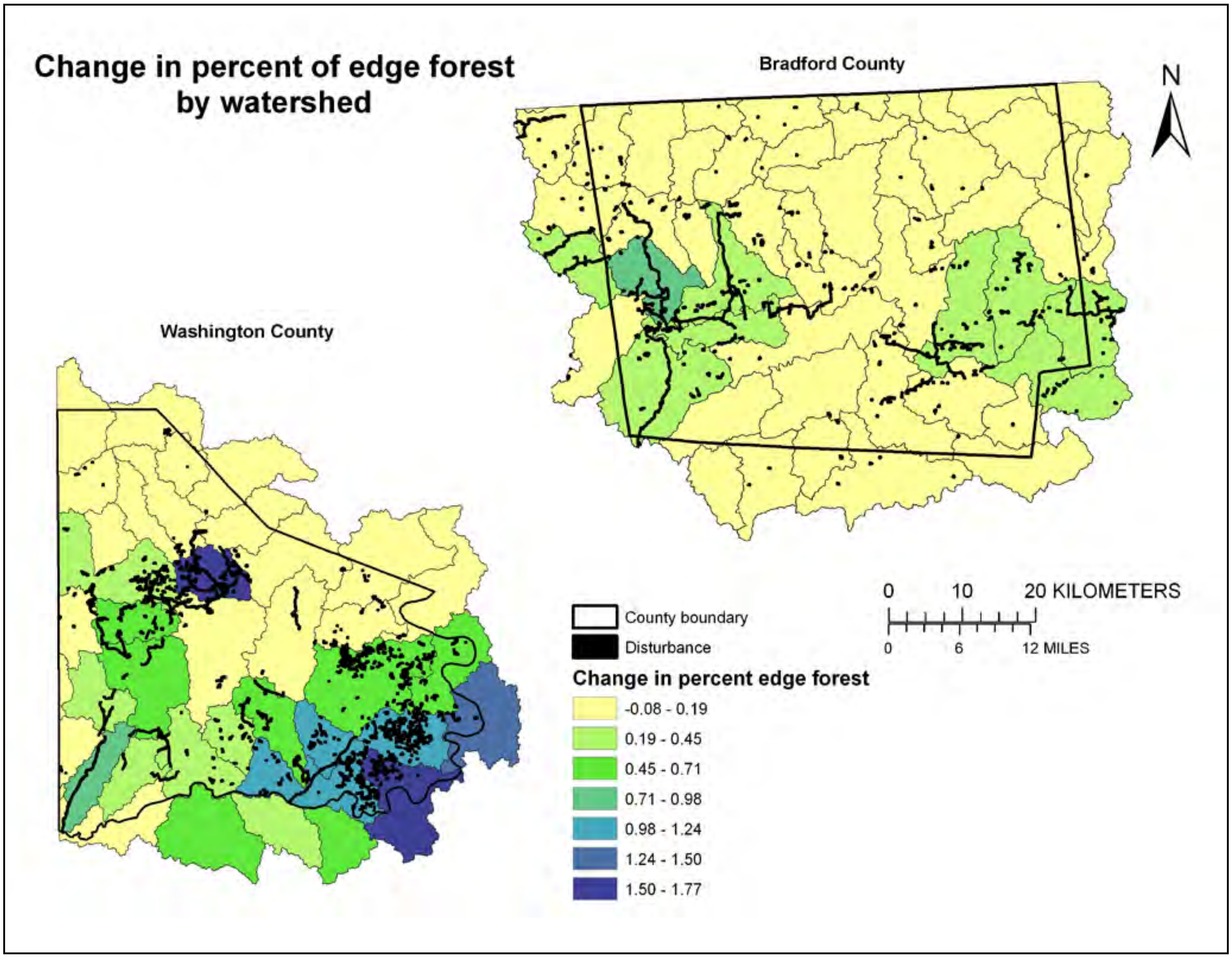

**Figure 13.** Change in percent of edge forest by watershed in Bradford and Washington Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Atlas [(http://viewer.nationalmap.gov/viewer) (U.S. Geological Survey, 2011)].

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For those of you who remember, I'm the former Commissioner of the New York City Department of Environmental Protection and I've often been before this Commission in a couple of decades past.
I must say I presume we would all be rather dealing with the issues we used to deal with then - releases from Cannonsville and Popackton, trout, passing flows of Montague rather than be stuck with fracking. But history has given us fracking, and like all people in public life today we have to look at global warming, 'cause global warming is what we're gonna leave our children and our grandchildren's children and we will all be responsible for the mark of Cain that will be left on this generation if we do not in our own decision-making consider that.
Now, I'd like to echo what David Berg said about the measured approach the DRBC is taking to this. It is consistent with my best recollections of the DRBC and I hope you continue to do so.
It is to that measured approach I wish to appeal.
I want to start with the experience that's going on in Northen Virginia at the moment where there is a controversy over whether or not to allow fracking in the George Washington National Forest which is the headwaters for many of the water sources for Washington DC and Northern Virginia.
The major water purveyors in that area, such as the Fairfax County Water Authority and the Washington Aquaduct Company have all come out in opposition to fracking in the national forest unless and until it is scientifically demonstrated that fracking will not have an environmental impact on the water supply functions of that forest.
Now, the issue of science has been bitterly debated for the last five years, and I would like to suggest to this Commission that the fact that it has taken five years for the industry to FAIL to demonstrate that this is a scientifically successful thing is a fact worth thinking about.
I have dealt with many of the industry claims, such as for example that the shale level is impervious and therefore there can be no migration of pollution up through the shale.
As DEP Commissioner I looked at a lot of the construction data in terms of the shale we went through for our water tunnels, there were fissures as long as seven miles.
As you heard today, there's a great deal of evidence that the claims of the industry that this is a safe process don't exist.
And in fact I'm relatively confident, that if they did exist half the phds on the planet would be getting research grants from the fracking industry to produce the papers that would make the link that they have not linked.
Instead, as you heard David Berg said, we get an industry that is telling us we gotta gut the endangered species act, that the EPA should not collect data on methane emissions
from [gas] plants and in short, this is not a group of people that seem to welcome quote, science, unquote.
Now, the DRBC is legally charged with protecting the water supply.

Now, many people approach the issue of gas fracking as a cost - benefit tradeoff. What I hope much of the testimony you've heard here will demonstrate that even if you believe that is your institutional mission, which I think is incorrect, the truth of the matter is the benefits don't exist. You heard about the problems of methane and global warming, you've heard about the issues of health; You heard about the damage to the environment. You heard about the whole question of property values. As a bio-politician, I'm gifted with second sight on this one. This is going to be the issue that puts a ban in New York State over the top as people start adding up what the inability to get household insurance and mortgage coverage is going to mean for them.

But, most of all, what I want to stress for you given my limited time, is take a good look at this map. This is a map of the perfect landscape for gathering water - for gathering clean, abundant drinking water. [showed map of DRB with forests indicated - ADD link here to this kind of map]

This will not be the same kind of map if you have gas fracking tearing this region apart with acres and acres of pads, lots of roads, lots of pollution...

This is what this debate is really all about. Are we going to preserve this landscape that as I say is a perfect landscape for the water that serves New York City, that serves Philadelphia, that serves many towns along the Delaware River Basin - or are we going to sacrifice it to a process that has no benefit and demonstrated costs.

That leads me to what I believe you're going to be given a proposal from the people of the Delaware River Basin.

We're going to formally propose that this Commission permanently ban gas fracking in the Delaware River Basin; that gas fracking in the Delaware River Basin is inconsistent with your institutional mission and is inconsistent with the highest and best use of this landscape.

Basically, the state of New York has been wise enough to recognize that a water special landscape should have fracking kept out of it and I hope the DRBC thinks so as well.