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http://pubs.er.usgs.gov/publication/ofr20121154

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.

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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) |

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.

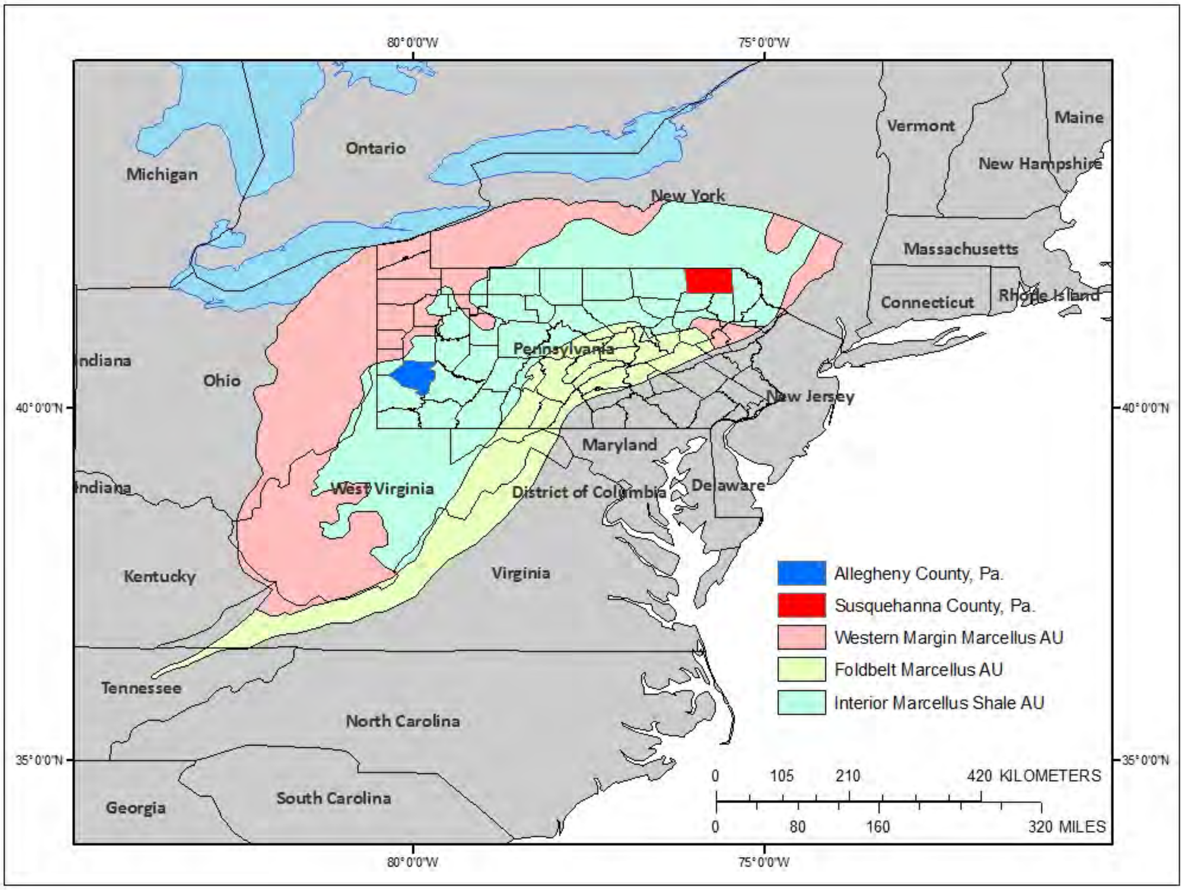

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus 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.

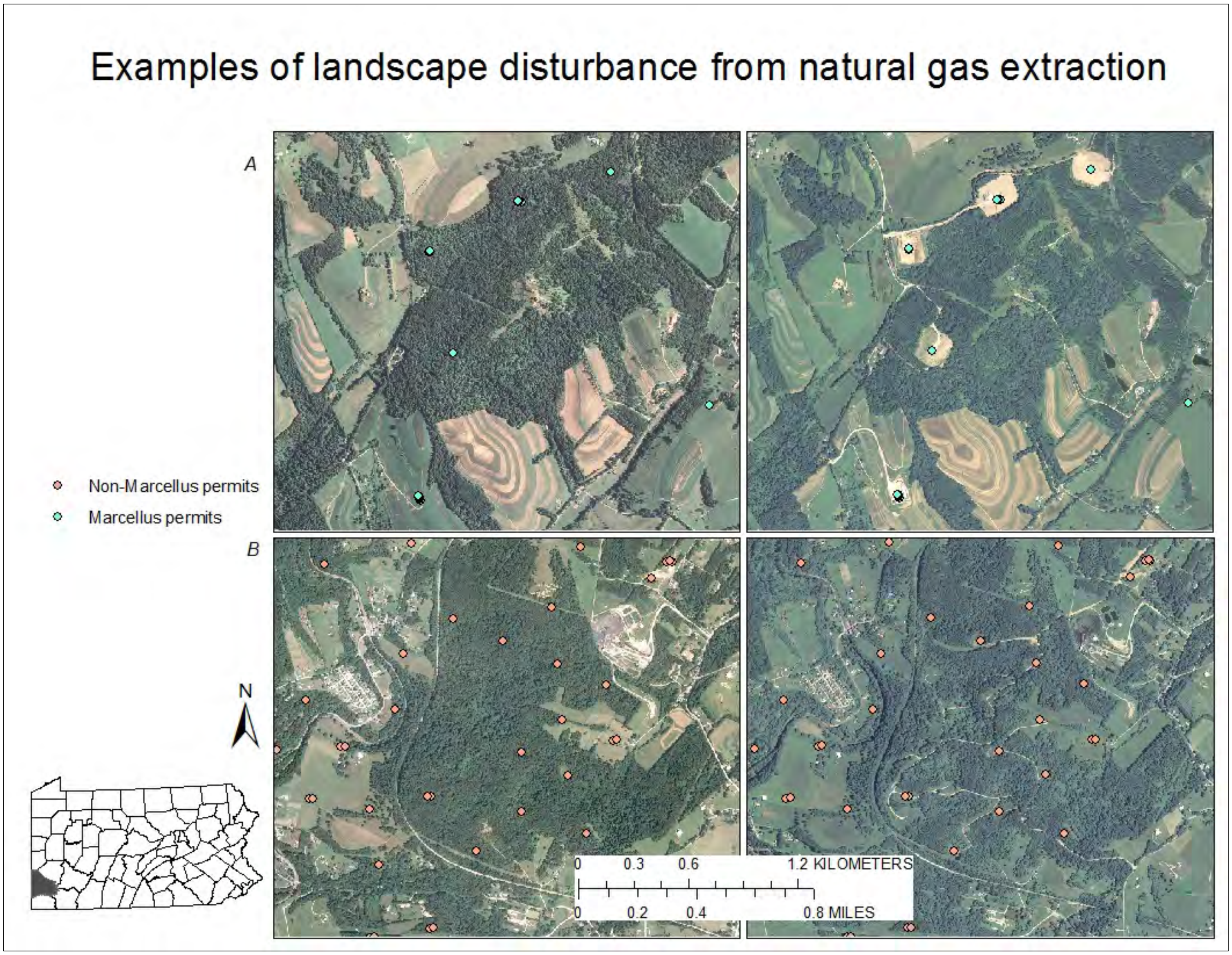

**Figure 2.** Examples of forested landscapes from Washington County, Pennsylvania, showing the spatial effects of roads, well pads, and pipelines related to (*A*) Marcellus Shale and (*B*) Conventional natural gas development. Left-hand side shows areas prior to development; right-hand side shows areas 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.

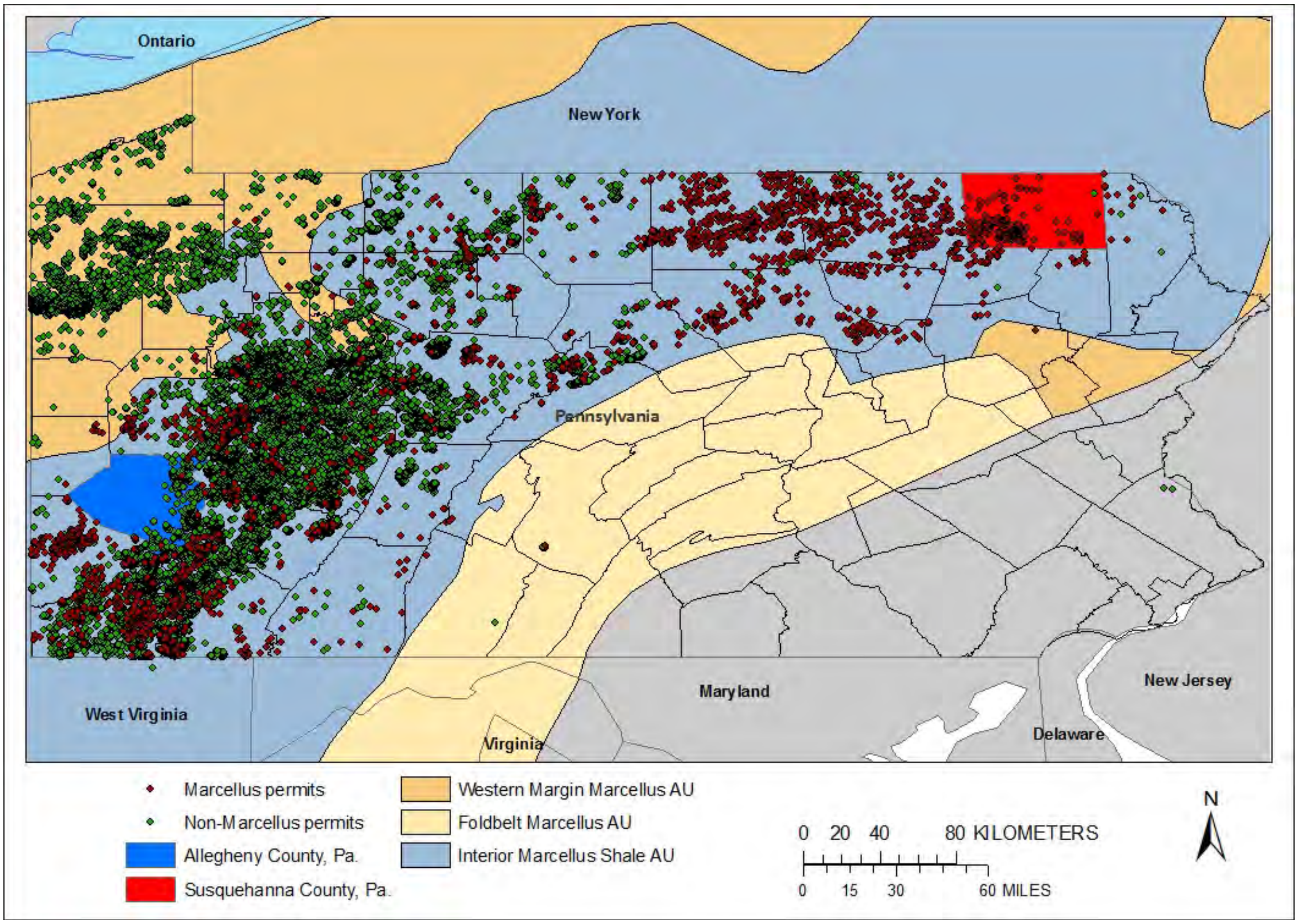

**Figure 3.** The distribution of Marcellus and non-Marcellus natural gas permits issued between 2004 and 2010 within Pennsylvania, the focal counties of Allegheny and Susquehanna, and their relation to the Interior Marcellus Shale assessment unit. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*)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

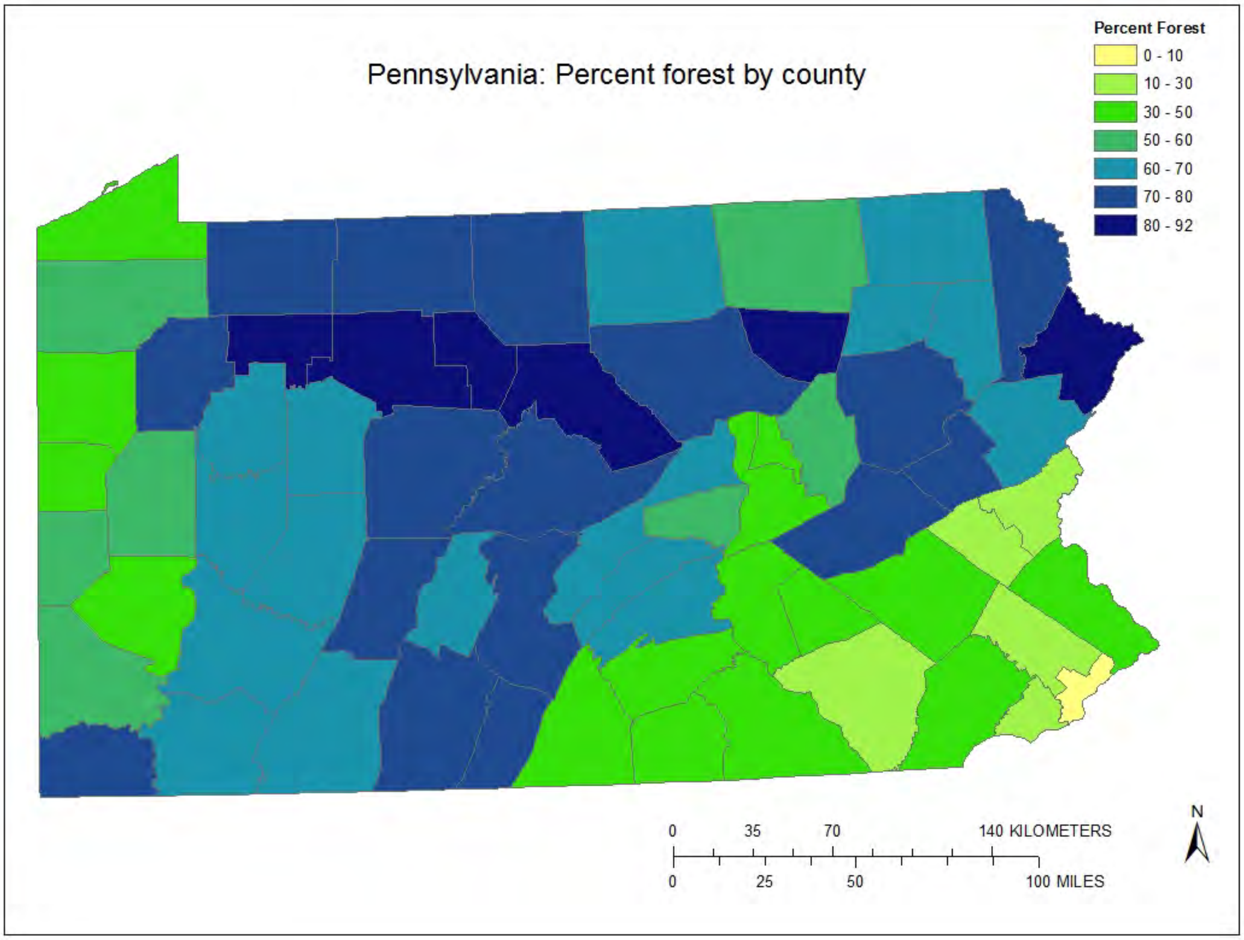

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Database. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer)* *(U.S.* Geological Survey, 2011a)].

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.

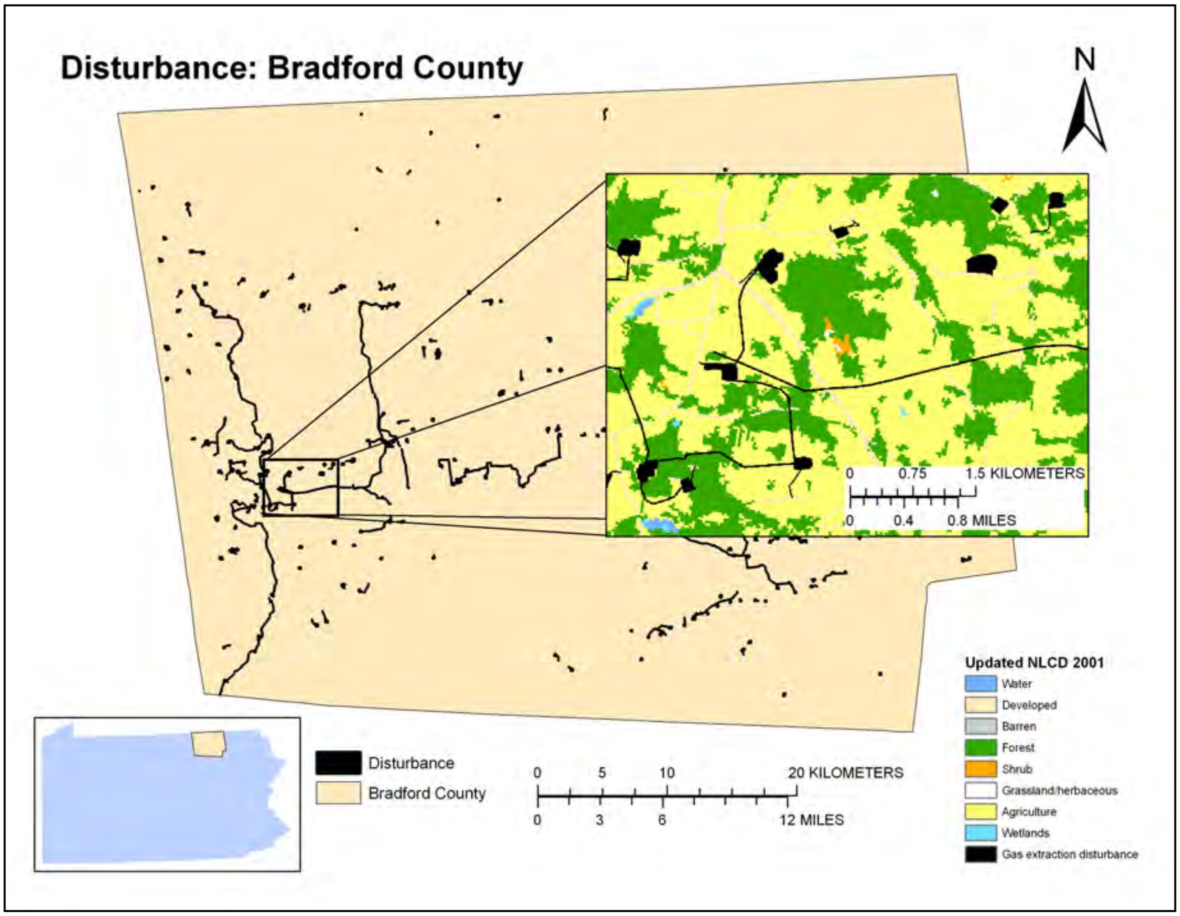

**Figure 5.** Example of a natural gas disturbance footprint from Bradford County, Pennsylvania, embedded within the National Land Cover Database (NLCD) 2001. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

## 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.

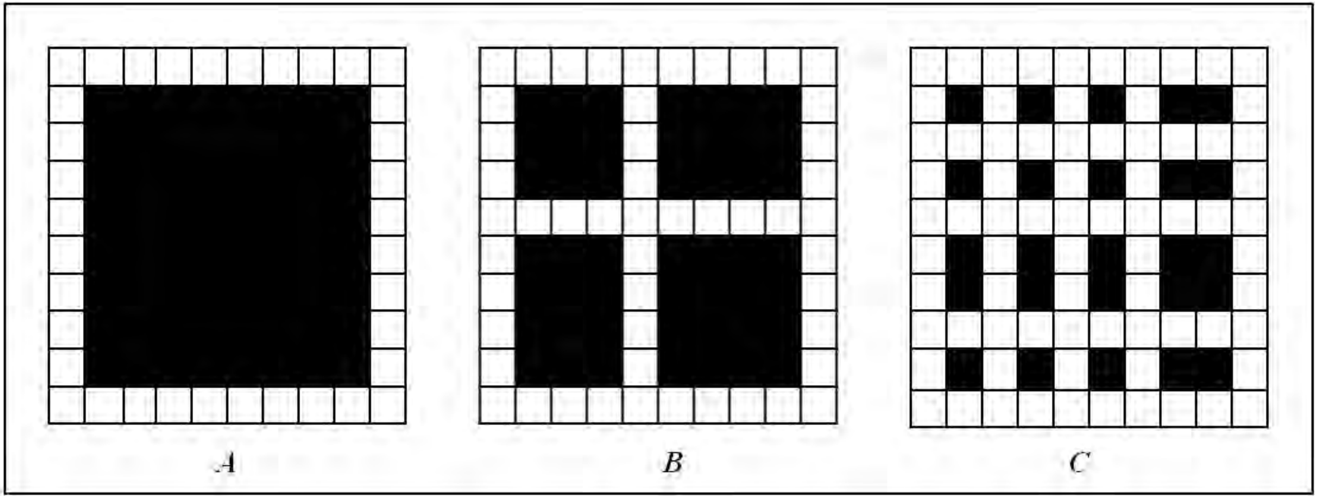

**Figure 6.** Conceptual illustration of interior forest and how this critical habitat is affected by linear disturbance. (*A*) High interior area, (*B*) Moderate interior area, and (*C*) Low interior area (Riitters and others, 1996).

## 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).

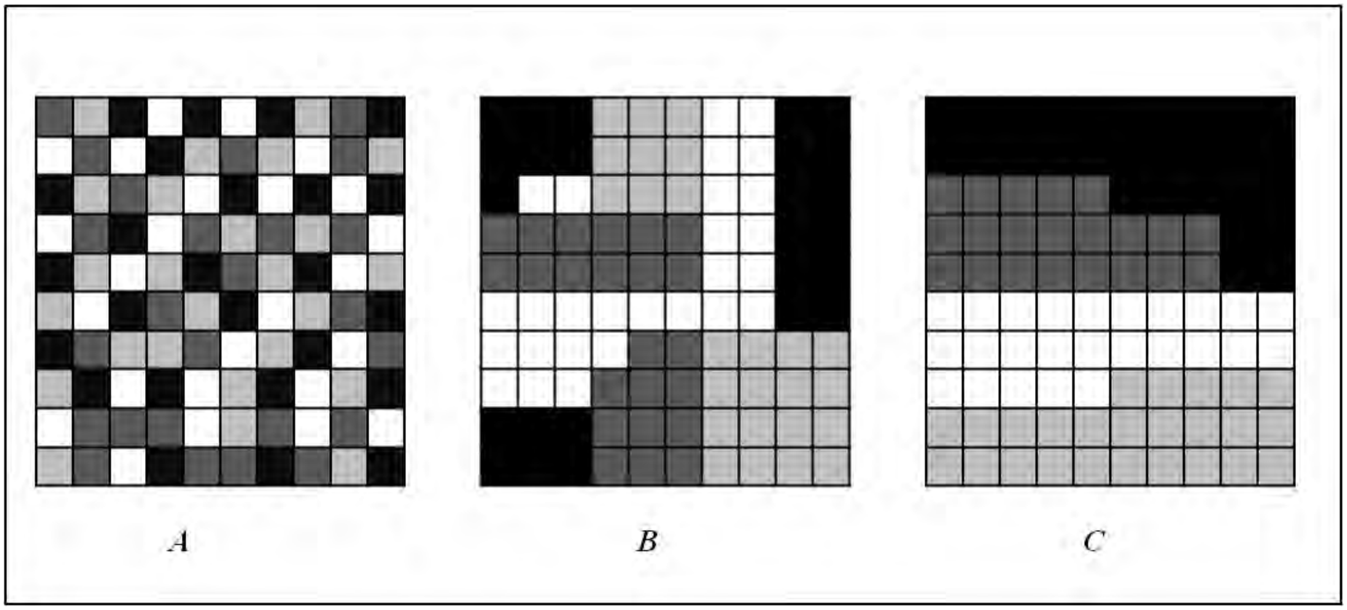

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or "clumped" to one another. *(A)* Low contagion, *(B)* Moderate contagion, and *(C)* High contagion (after Riitters and others 1996).

## 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.

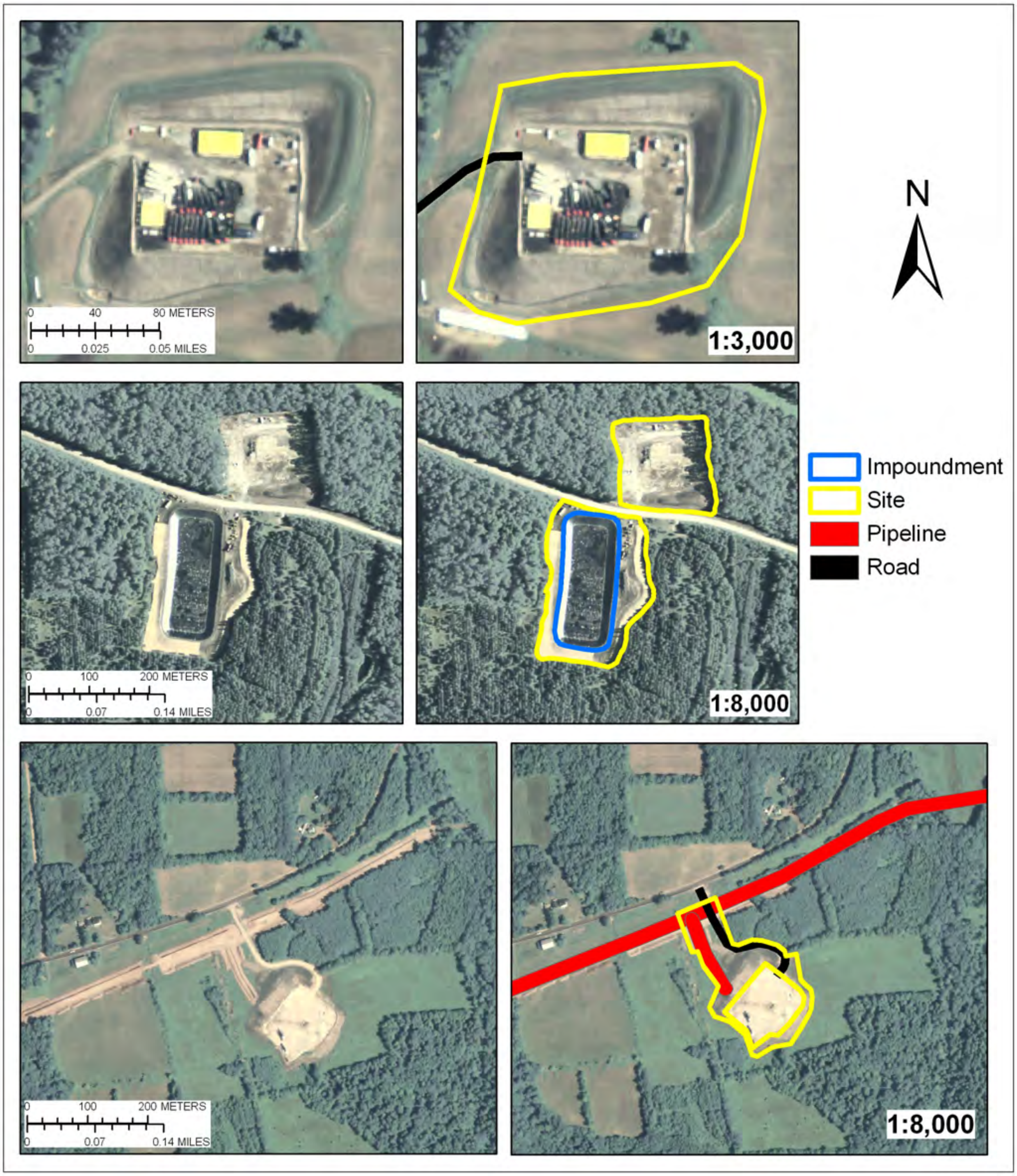

**Figure 8.** Examples of spatially explicit features of disturbance that were extracted from aerial photographs into a geographic information system (GIS) format.

## 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.

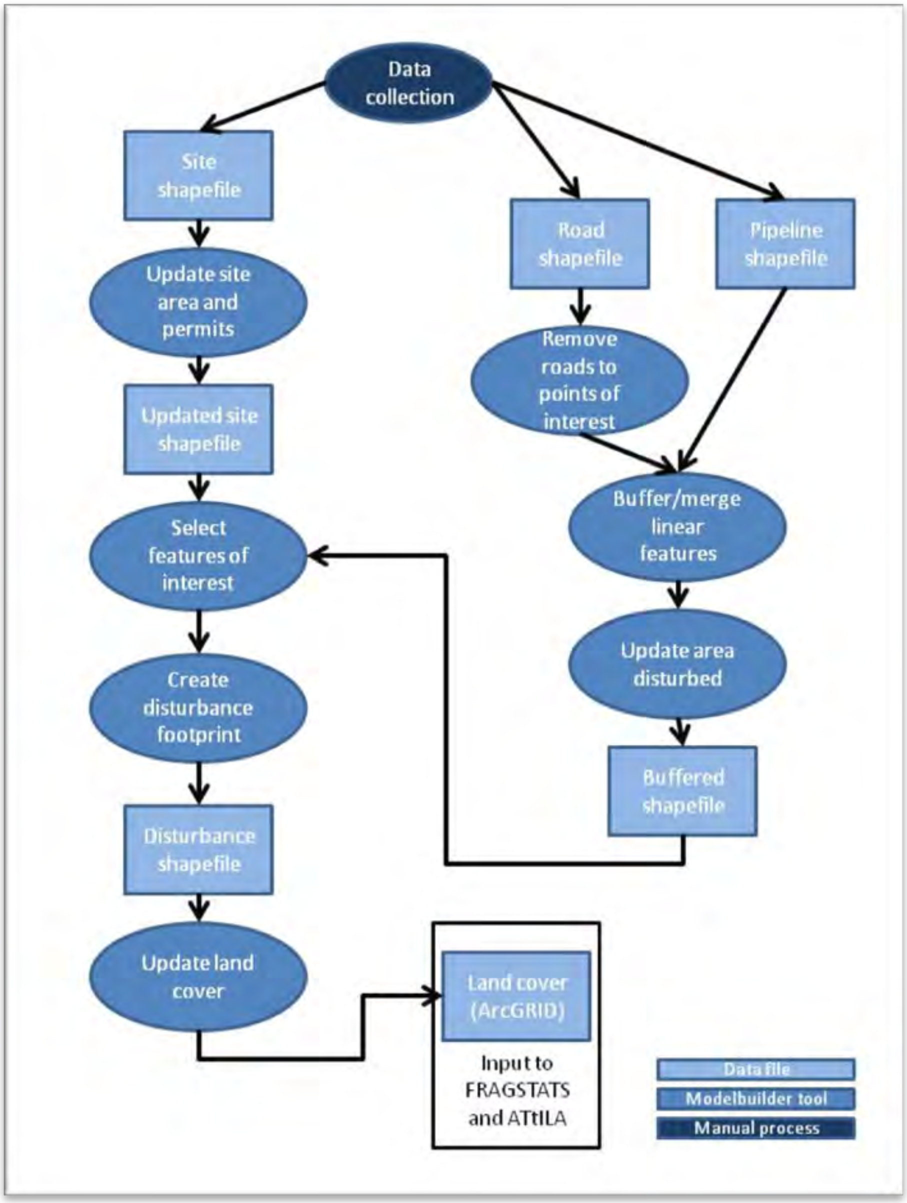

**Figure 9.** Workflow diagram for creating an updated land cover map. The workflow is implemented using ArcGIS ModelBuilder scripts to process the digitized data and embed in the resampled NLCD 2001.

### 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.

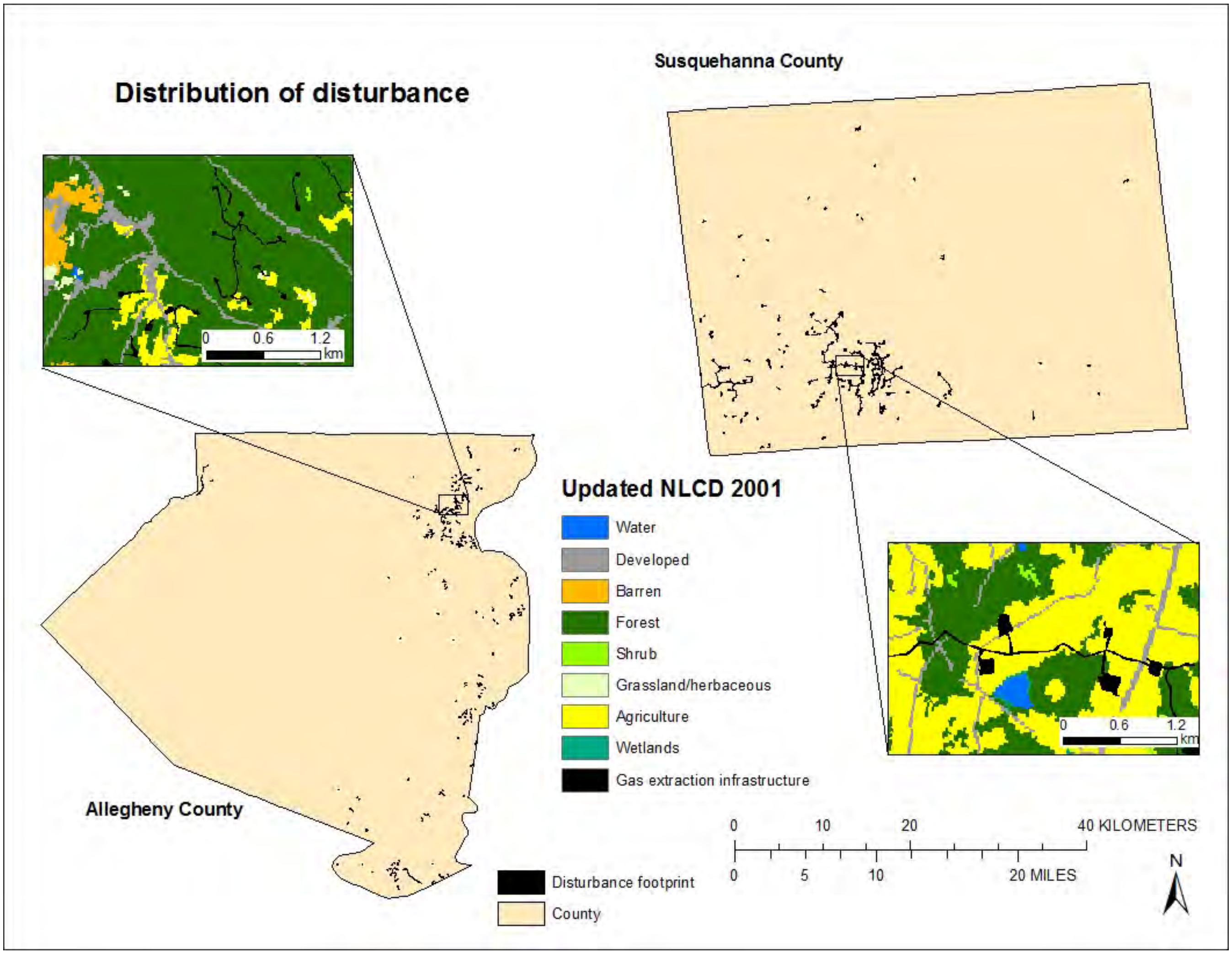

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Allegheny and Susquehanna Counties, Pennsylvania. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

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.

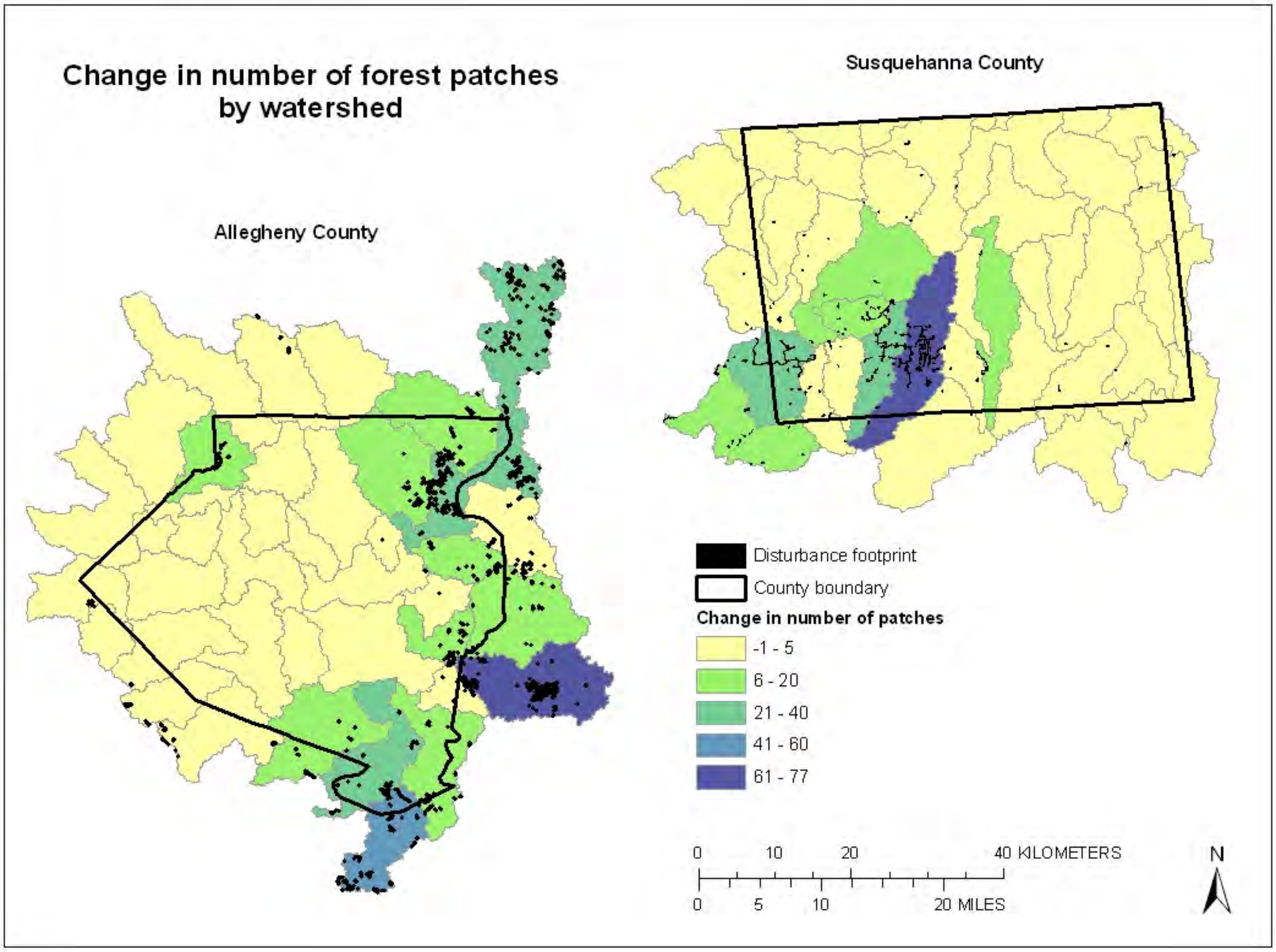

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing the increasing fragmentation in Allegheny and Susquehanna Counties, Pennsylvania. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

## 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 |

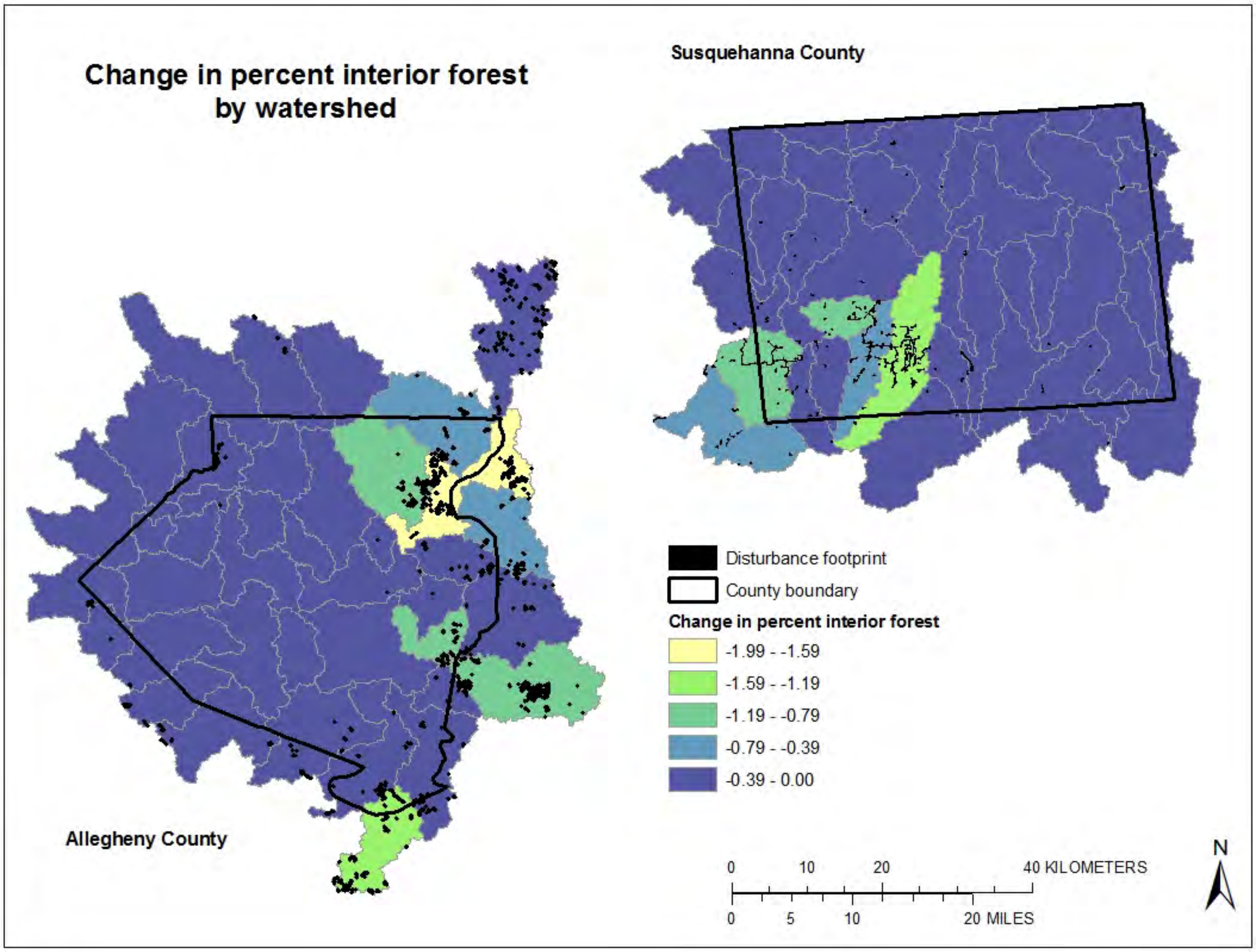

**Figure 12.** Change in percent interior forest by watershed in Allegheny and Susquehanna Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

## 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.

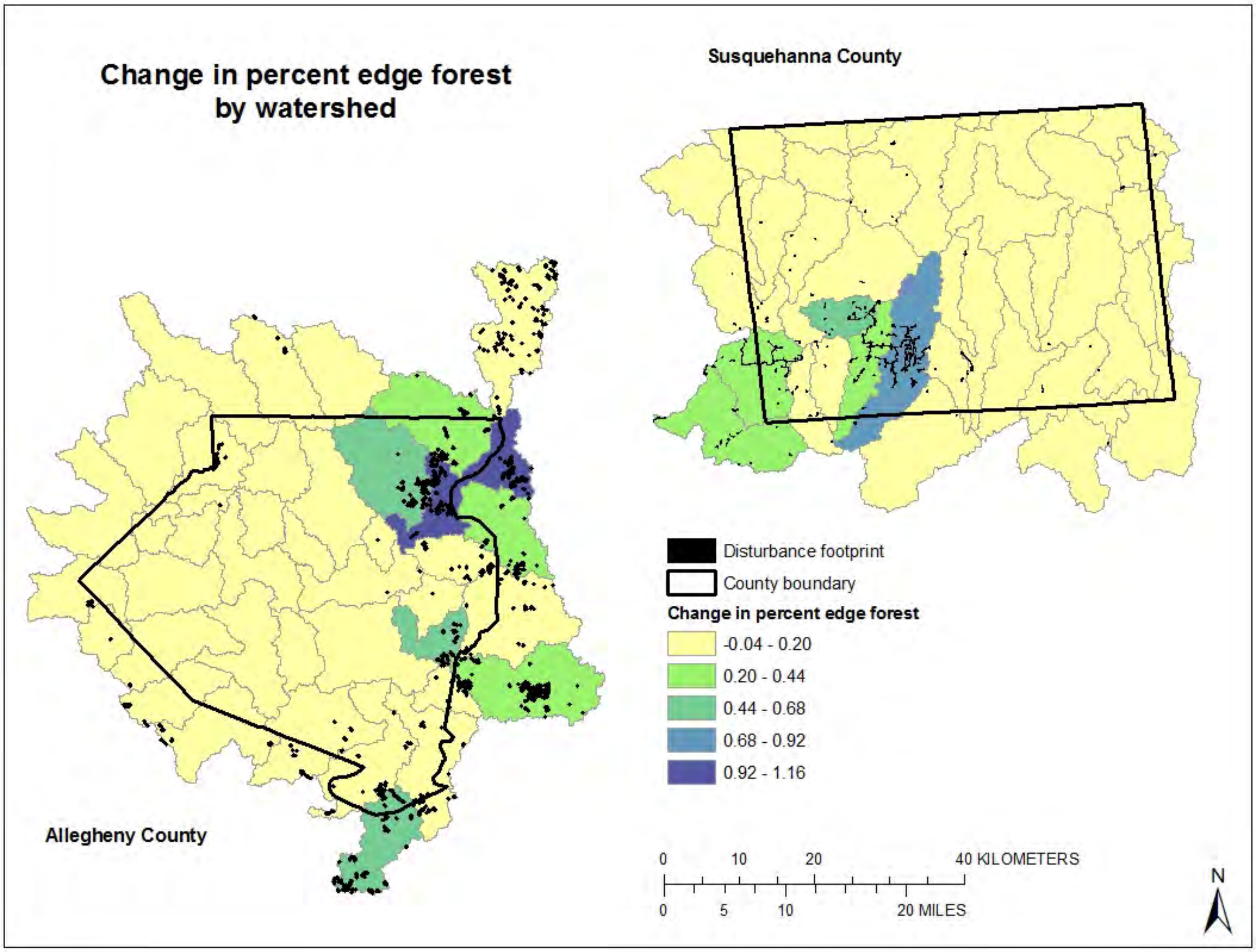

**Figure 13.** Change in percent of edge forest by watershed in Allegheny and Susquehanna Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011a)].

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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).

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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.

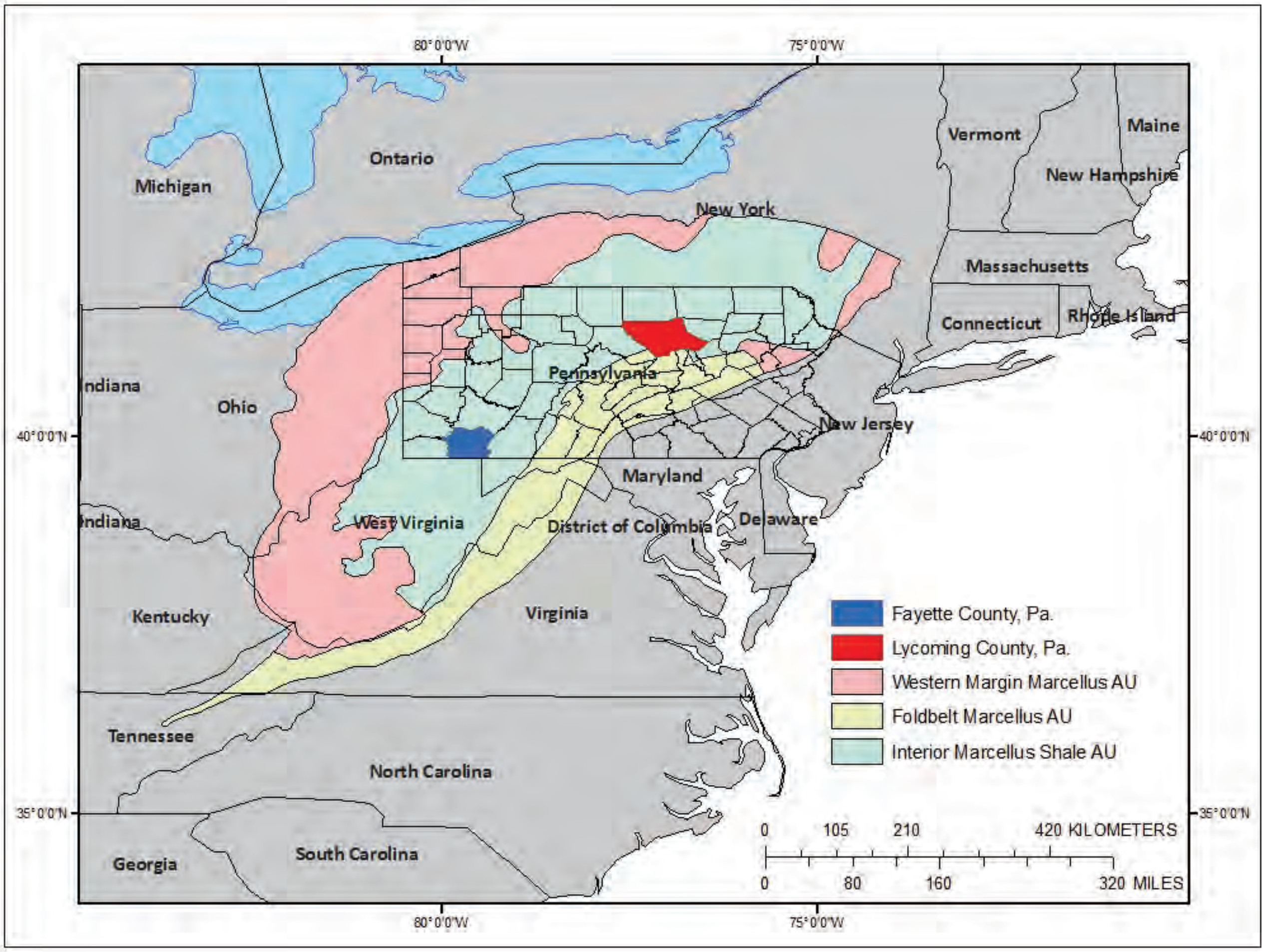

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus 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.

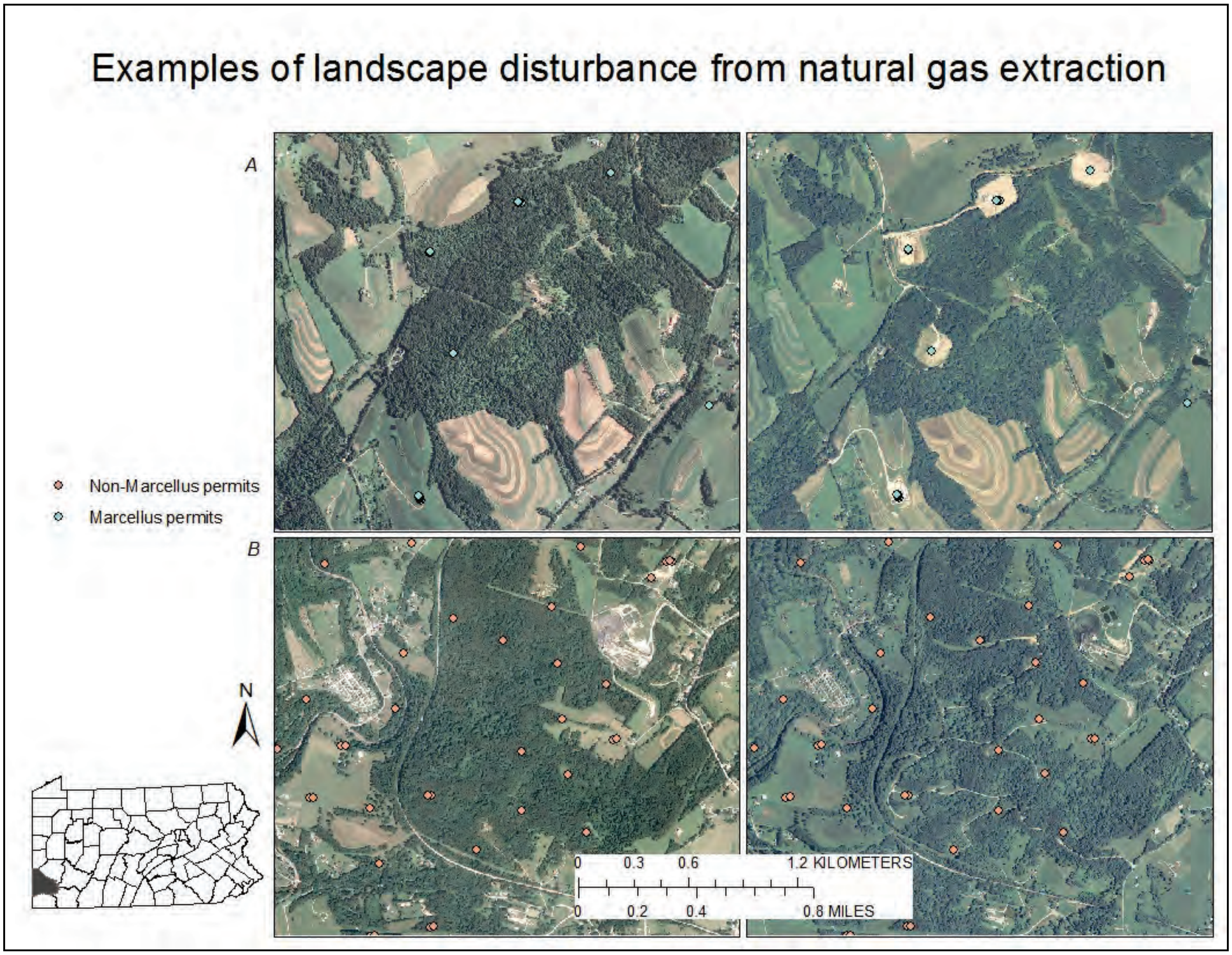

**Figure 2.** Example of forested landscapes from Washington County, Pennsylvania showing the spatial effects of roads, well pads, and pipelines related to (a) Marcellus Shale and (b) Conventional natural gas development. Inset shows the location of the images. Base-map data courtesy of *The National 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.

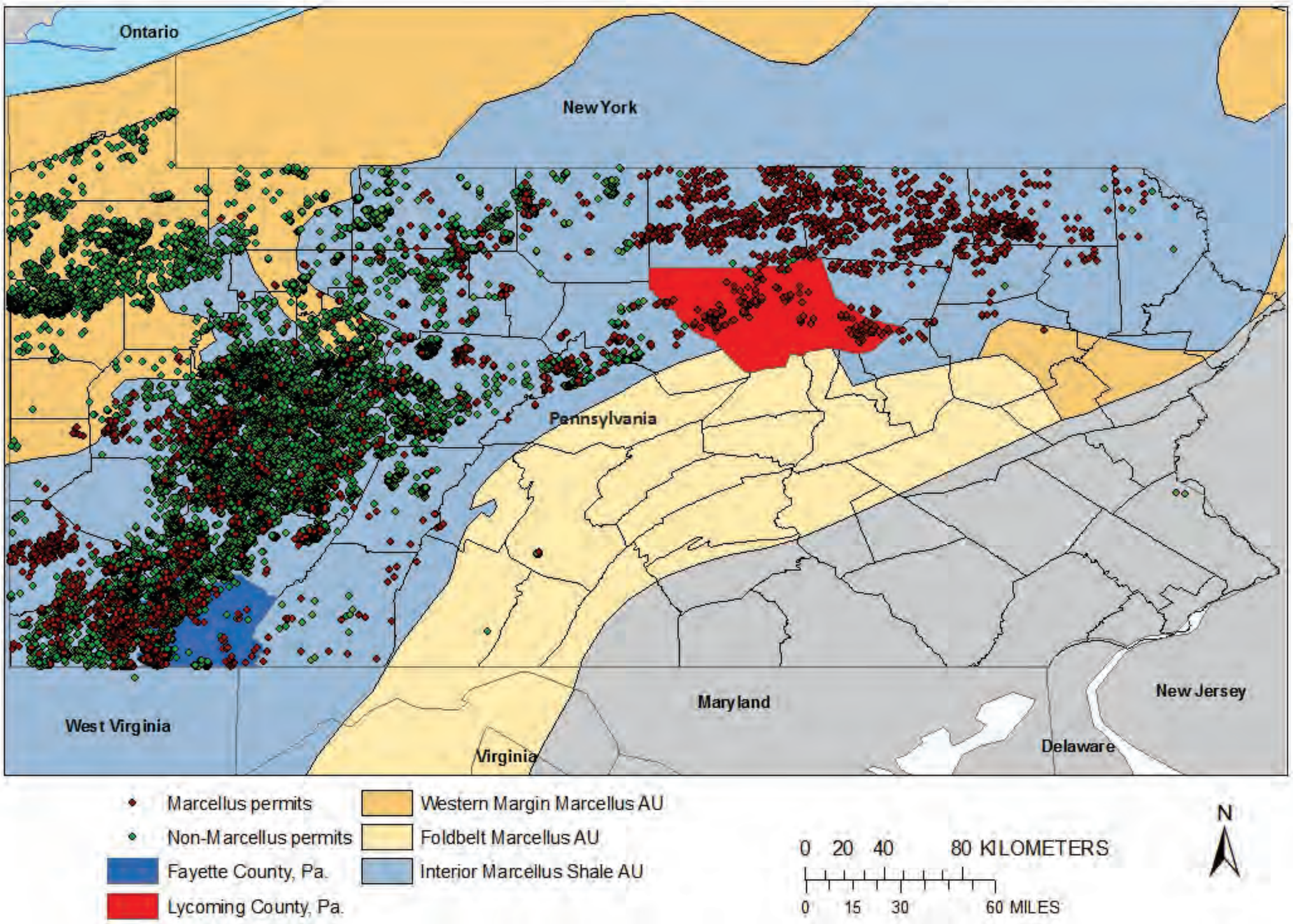

**Figure 3.** The distribution of Marcellus and non-Marcellus natural gas permits issued between 2004 and 2010 within Pennsylvania, the focal counties of Fayette and Lycoming, and their relation to the interior Marcellus Shale assessment unit. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer)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

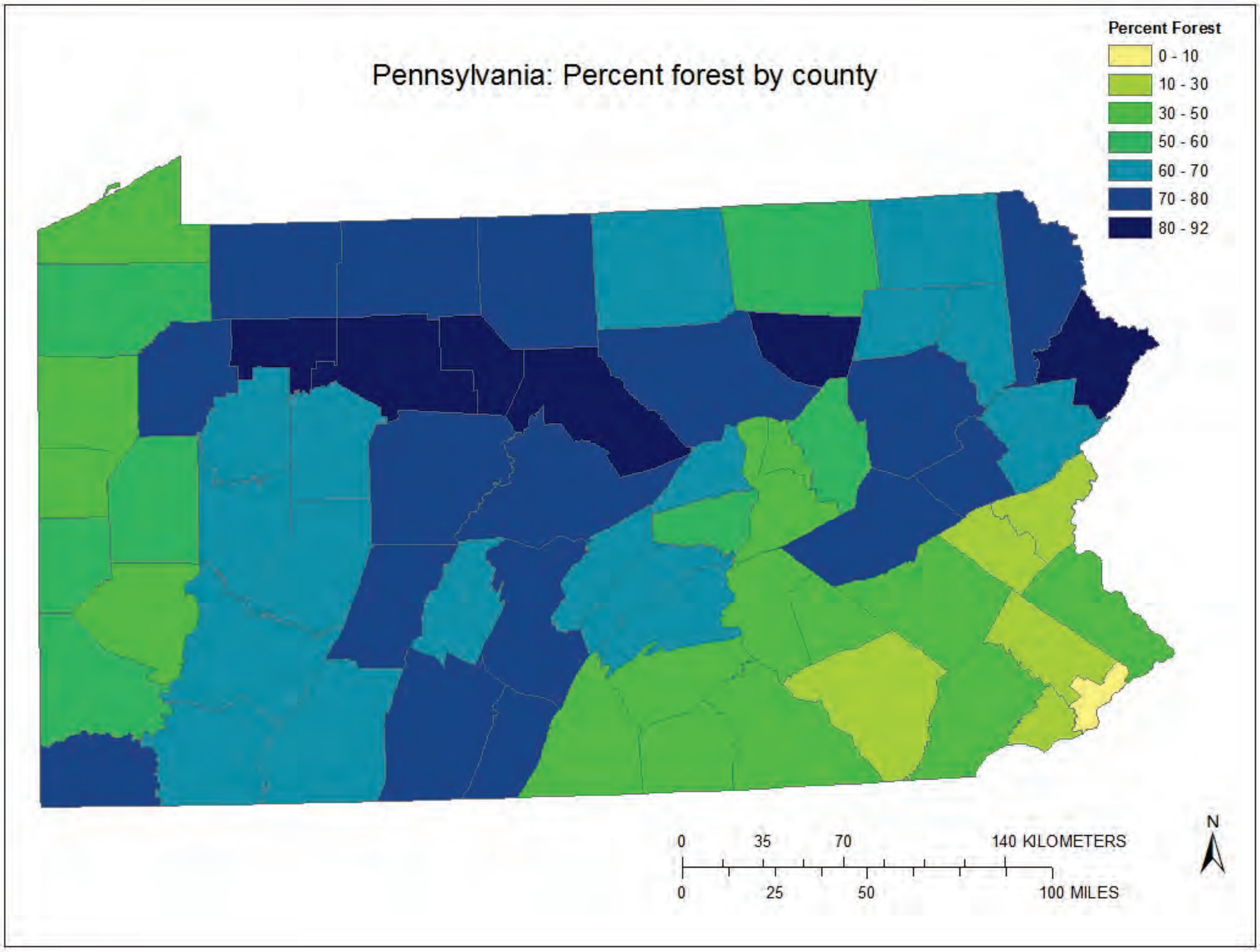

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Data. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

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.

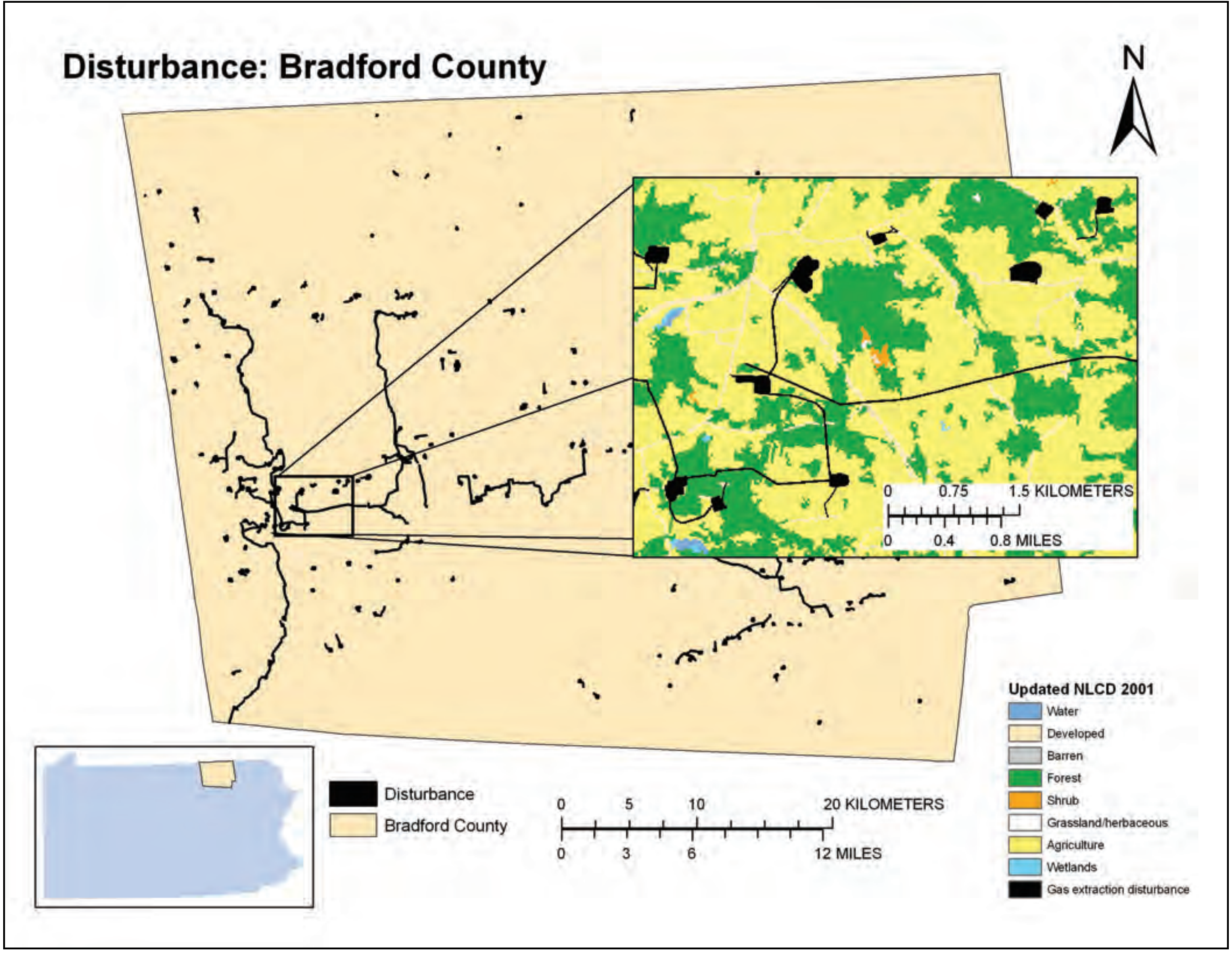

**Figure 5.** Example of a natural gas disturbance footprint from Bradford County, Pennsylvania, embedded within the National Land Cover Dataset (NLCD) 2001. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer*) (*U.S.* Geological Survey, 2011a)].

## 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.

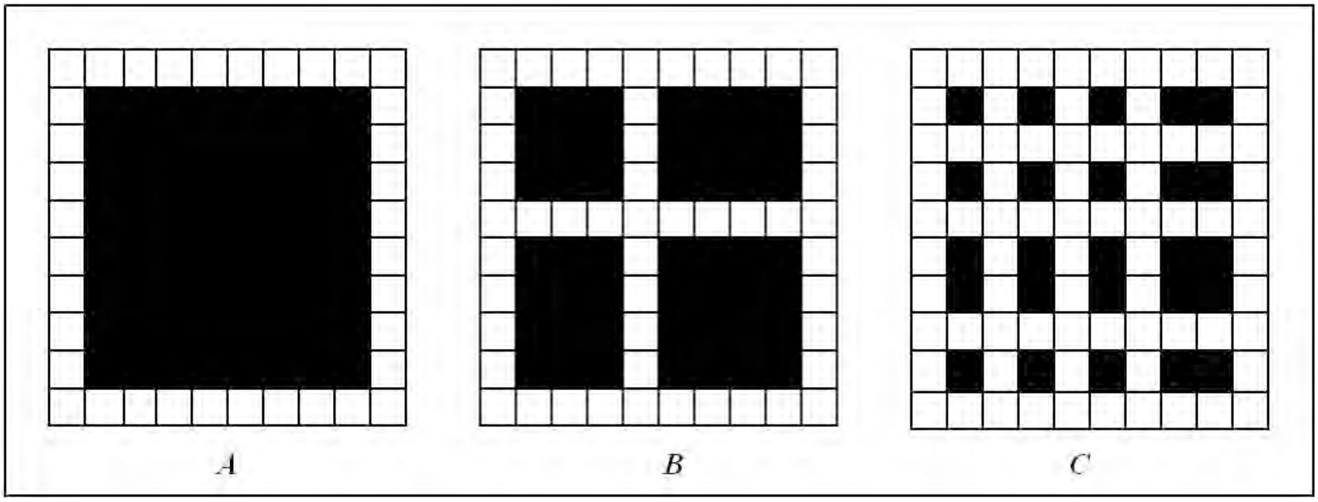

**Figure 6.** Conceptual illustration of interior forest and how this critical habitat is affected by linear disturbance. *A*, High interior area; *B*, Moderate interior area; and *C*, Low interior area (Riitters and others, 1996).

## 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 ($0<x\leq 100$, 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).

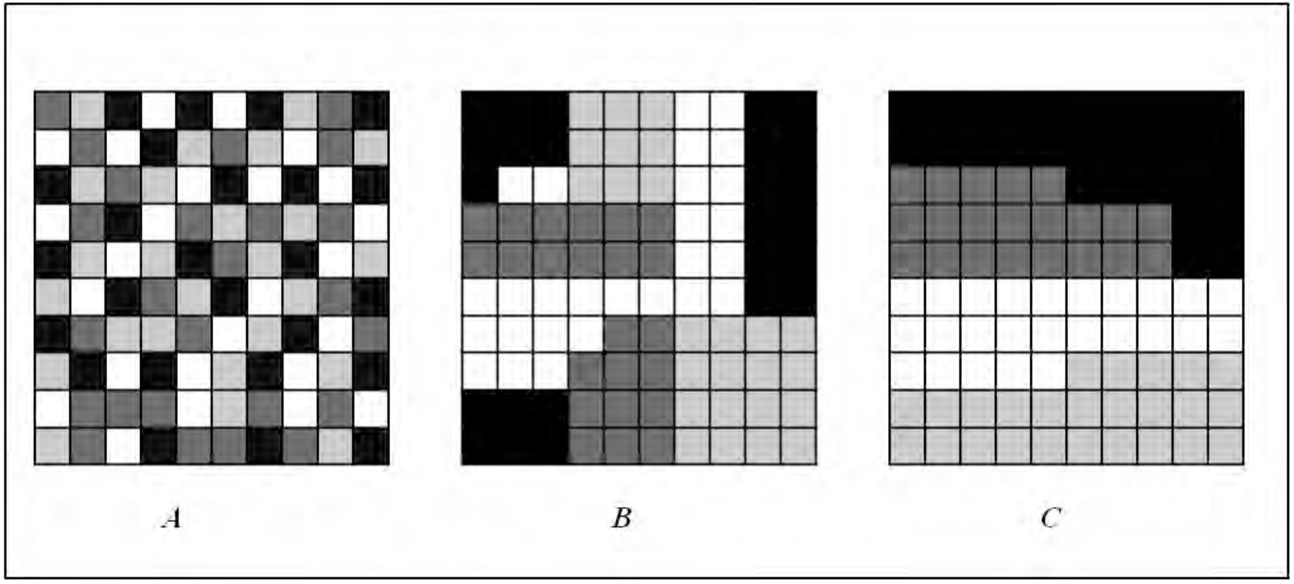

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or "clumped" to one another. *A*, Low contagion; *B*, Moderate contagion; and *C*, High contagion (after Riitters and others, 1996).

### 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.

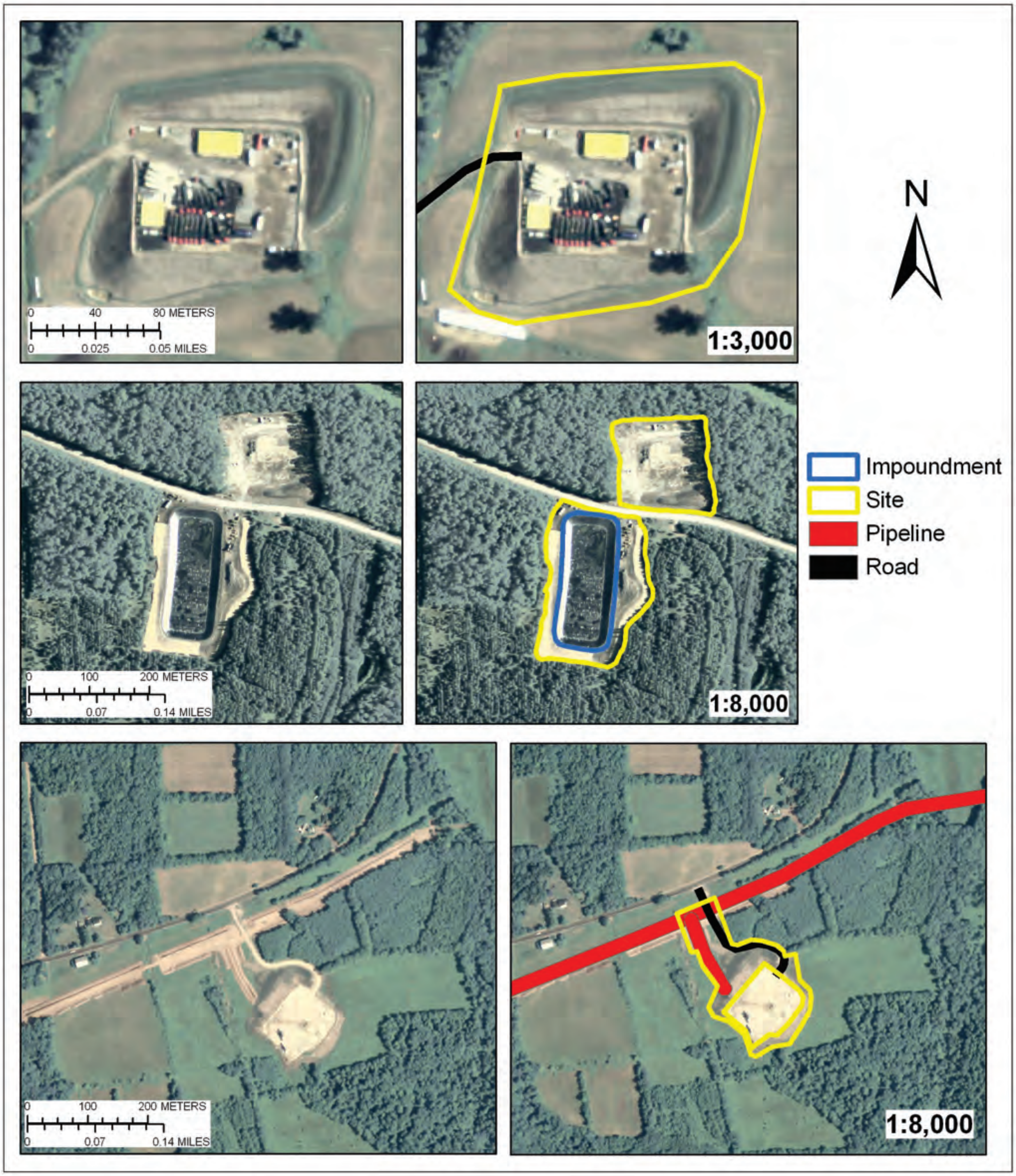

**Figure 8.** Examples of spatially explicit features of disturbance that were extracted from aerial photographs into a geographic information system (GIS) format.

## 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.

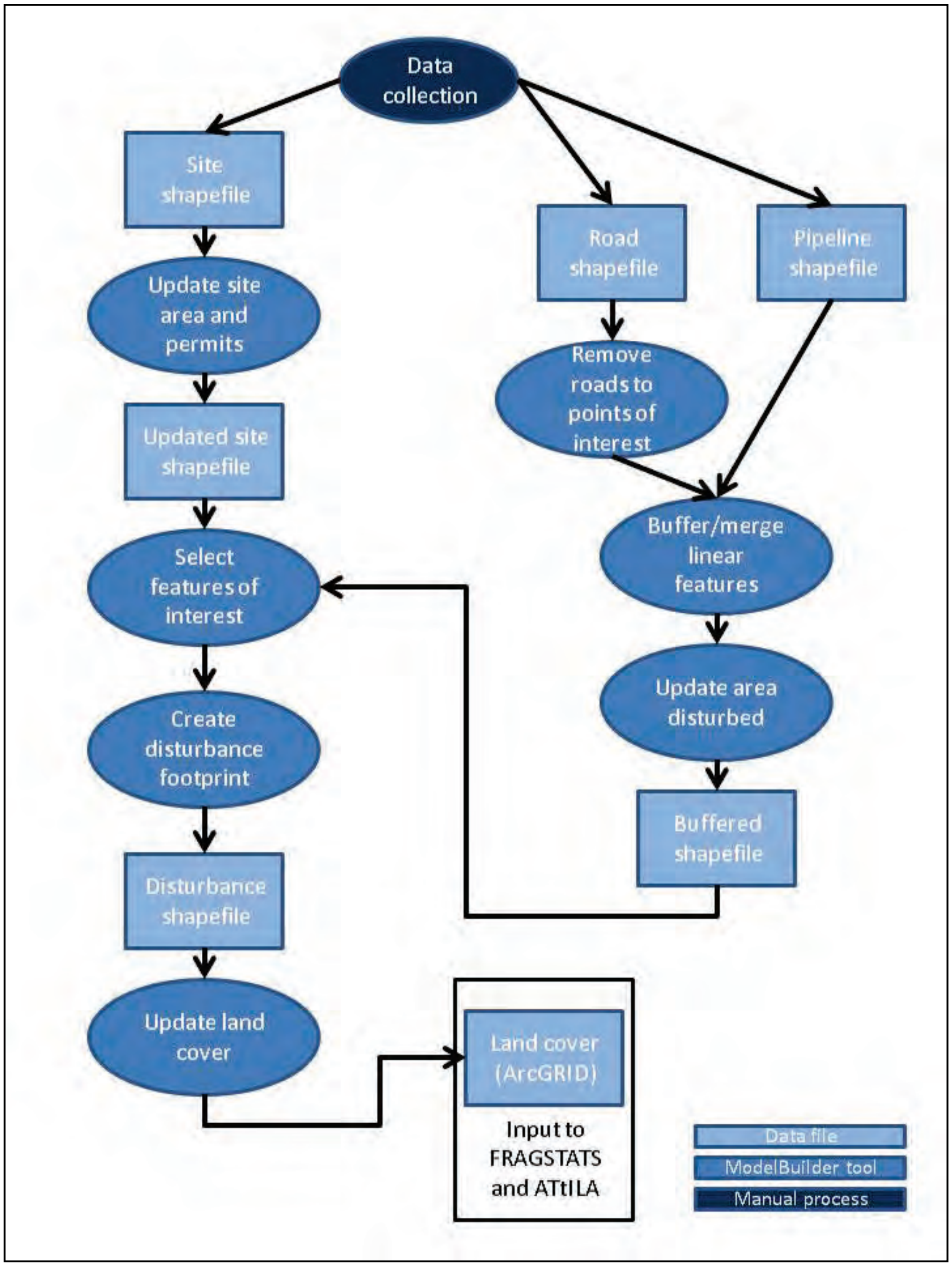

**Figure 9.** Workflow diagram for creating an updated land cover map. The workflow was implemented using ArcGIS ModelBuilder scripts to process the digitized data and embed results in the resampled NLCD 2001.

## 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.

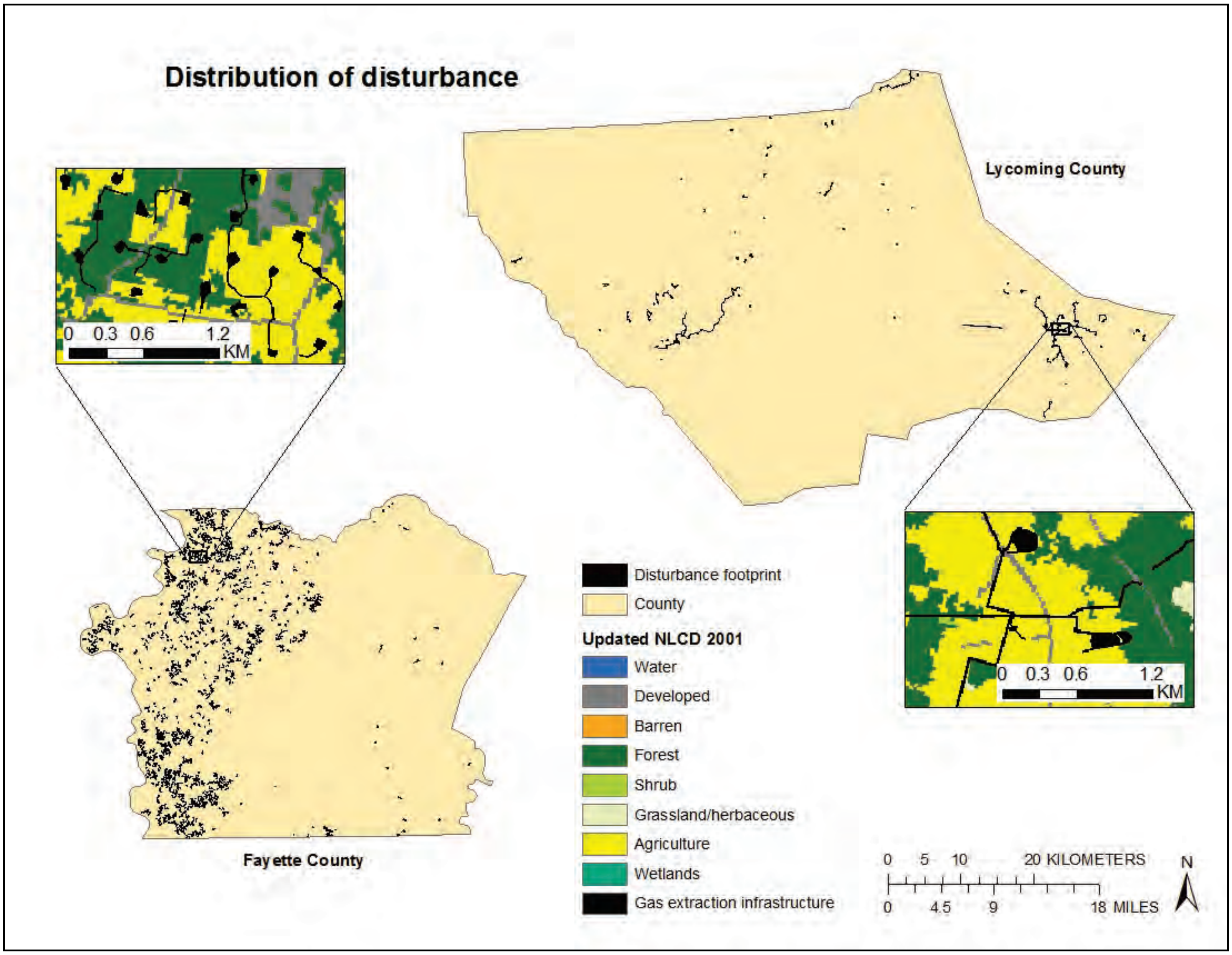

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Fayette and Lycoming Counties, Pennsylvania. Base-map data courtesy of The National Map [(*http://viewer.nationalmap.gov/viewer)* *(U.S*. Geological Survey, 2011a)].

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 ($1 \leq x \leq 2$) 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 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.

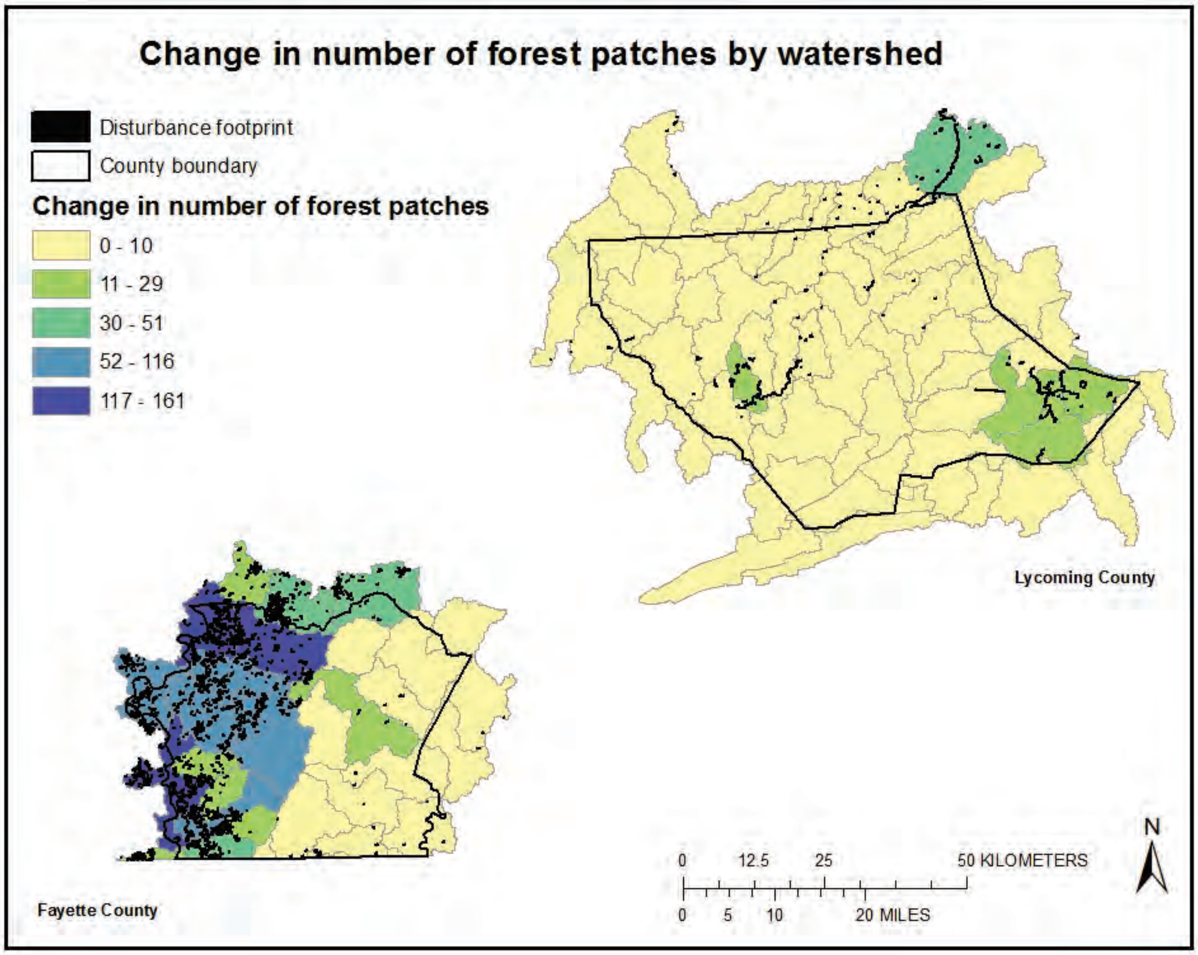

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing the increasing fragmentation in Fayette and Lycoming Counties, Pennsylvania. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S*. Geological Survey, 2011a)].

## 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 |

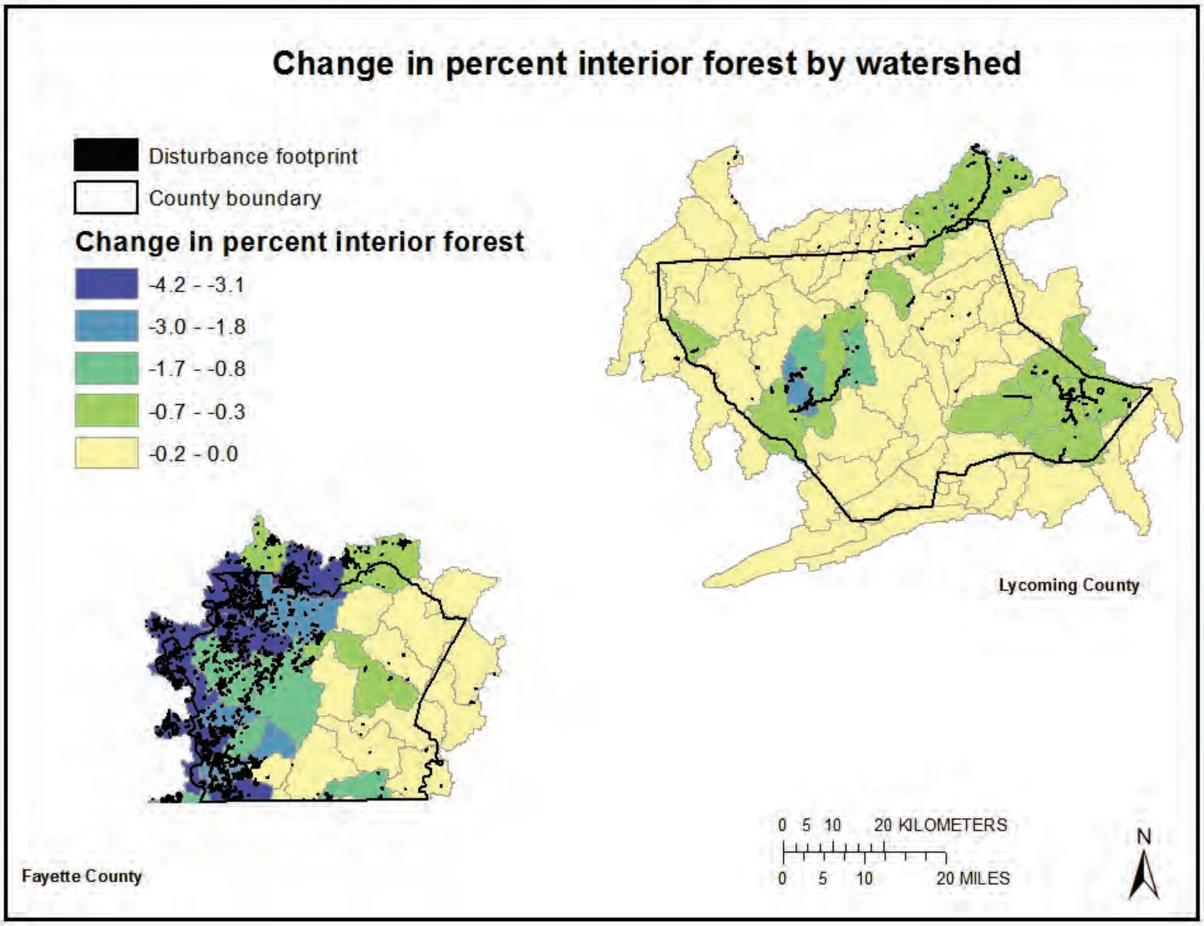

**Figure 12.** Change in percent interior forest by watershed in Fayette and Lycoming Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

## 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.

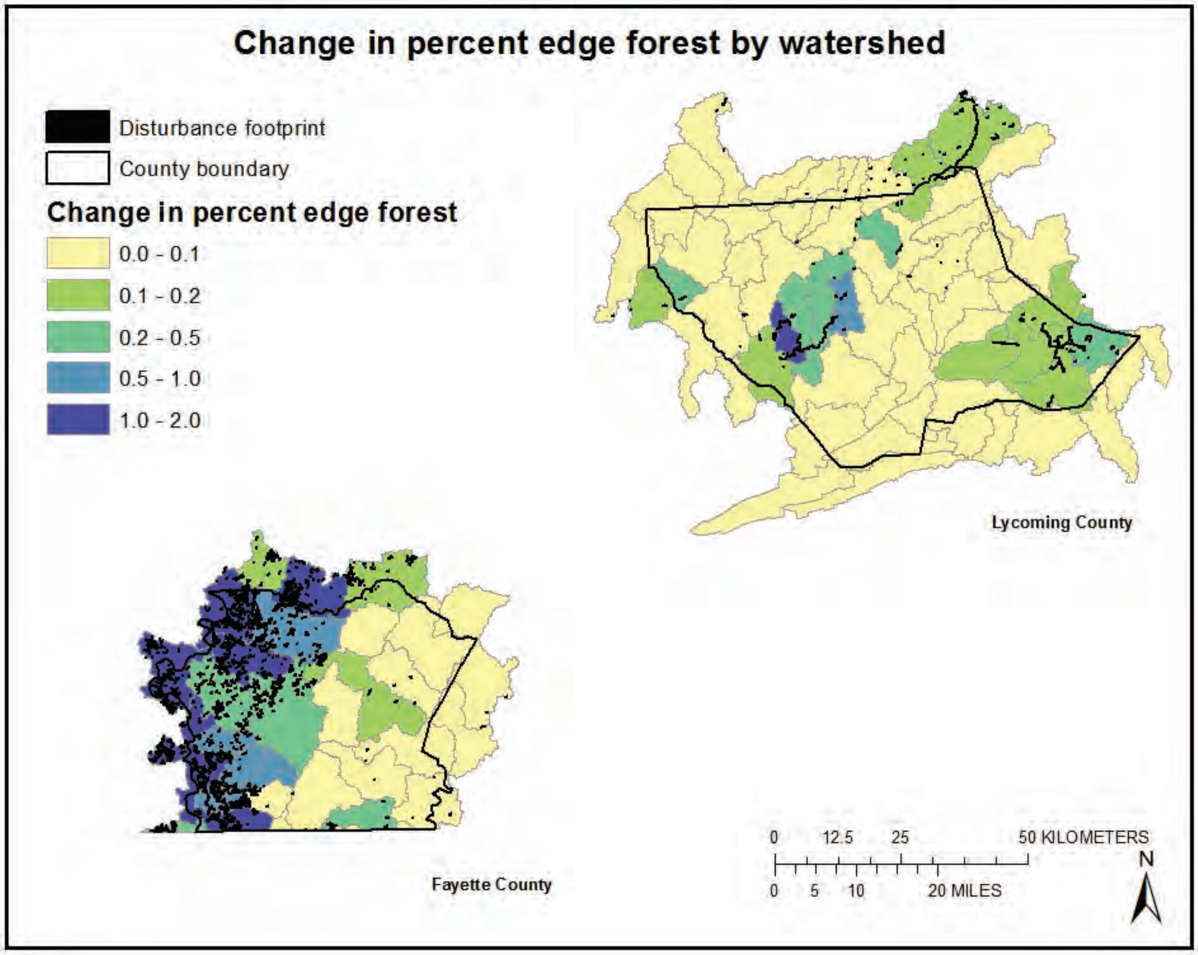

**Figure 13.** Change in percent of edge forest by watershed in Fayette and Lycoming Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of *The National Map* [(*http://viewer.nationalmap.gov/viewer) (U.S.* Geological Survey, 2011a)].

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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

Open-File Report 2012–1220

**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., 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.

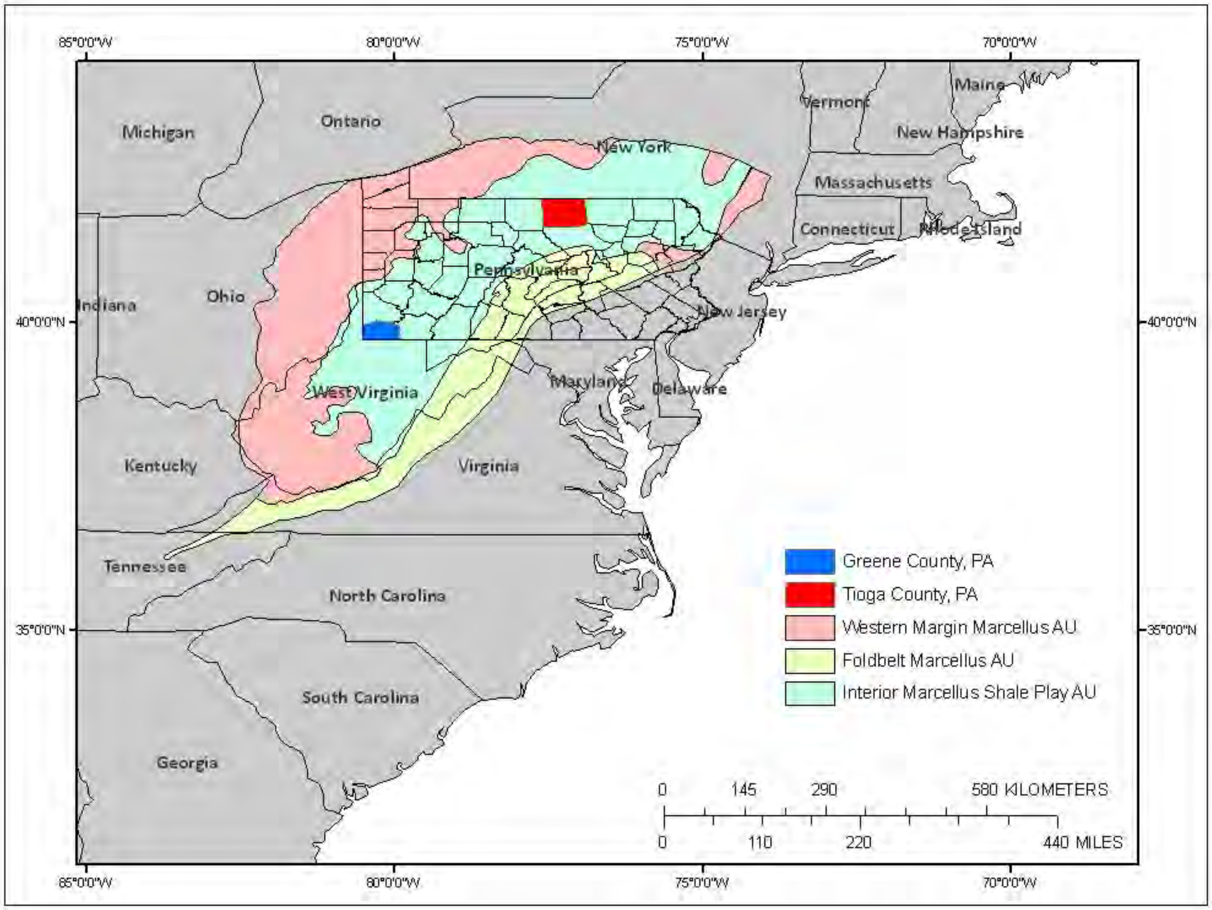

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus 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.

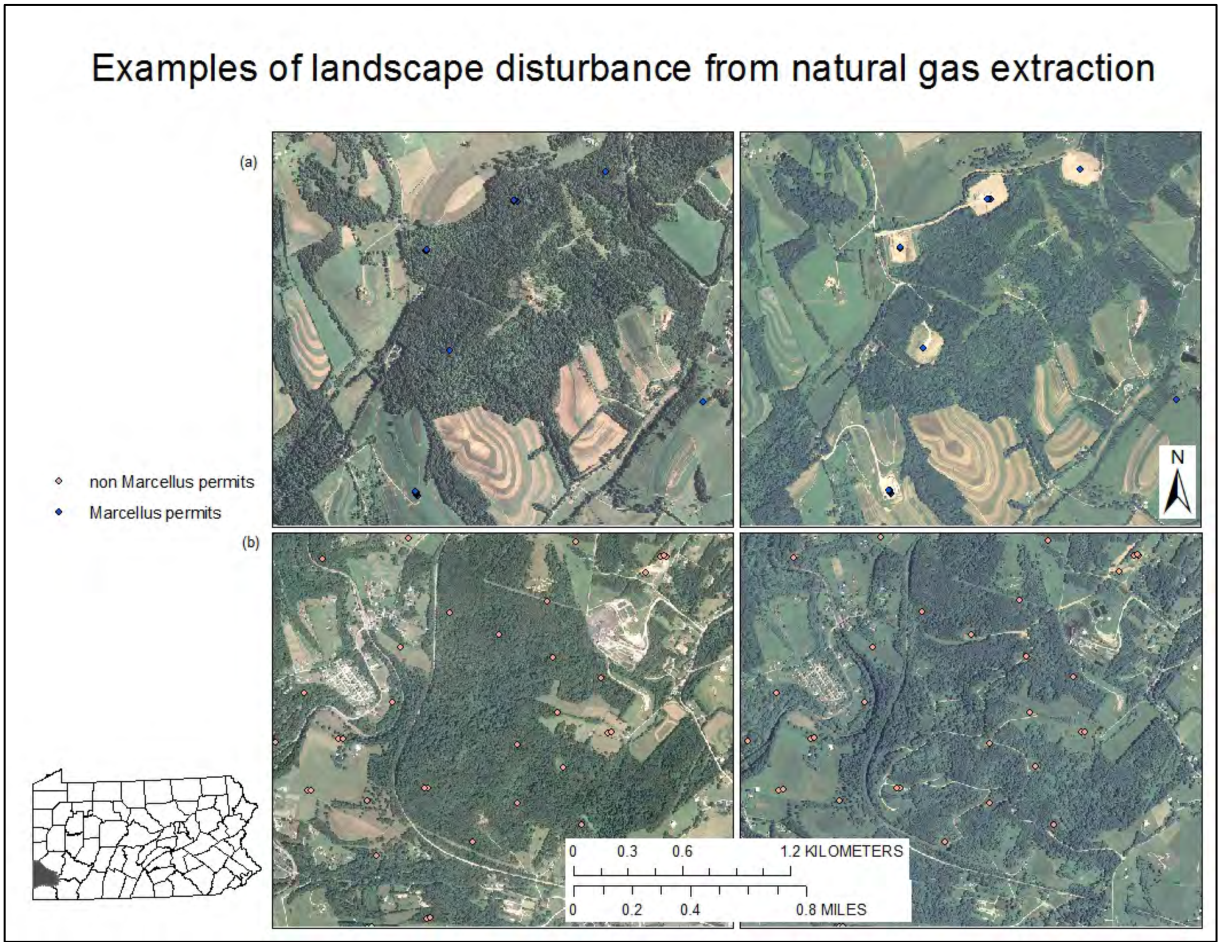

**Figure 2.** Examples forested landscapes in Washington County, Pennsylvania, showing the spatial effects of roads, well pads, and pipelines related to (a) Marcellus Shale and (b) conventional natural gas development. Inset shows the location of the image. Base-map data courtesy of the National Map [(*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.

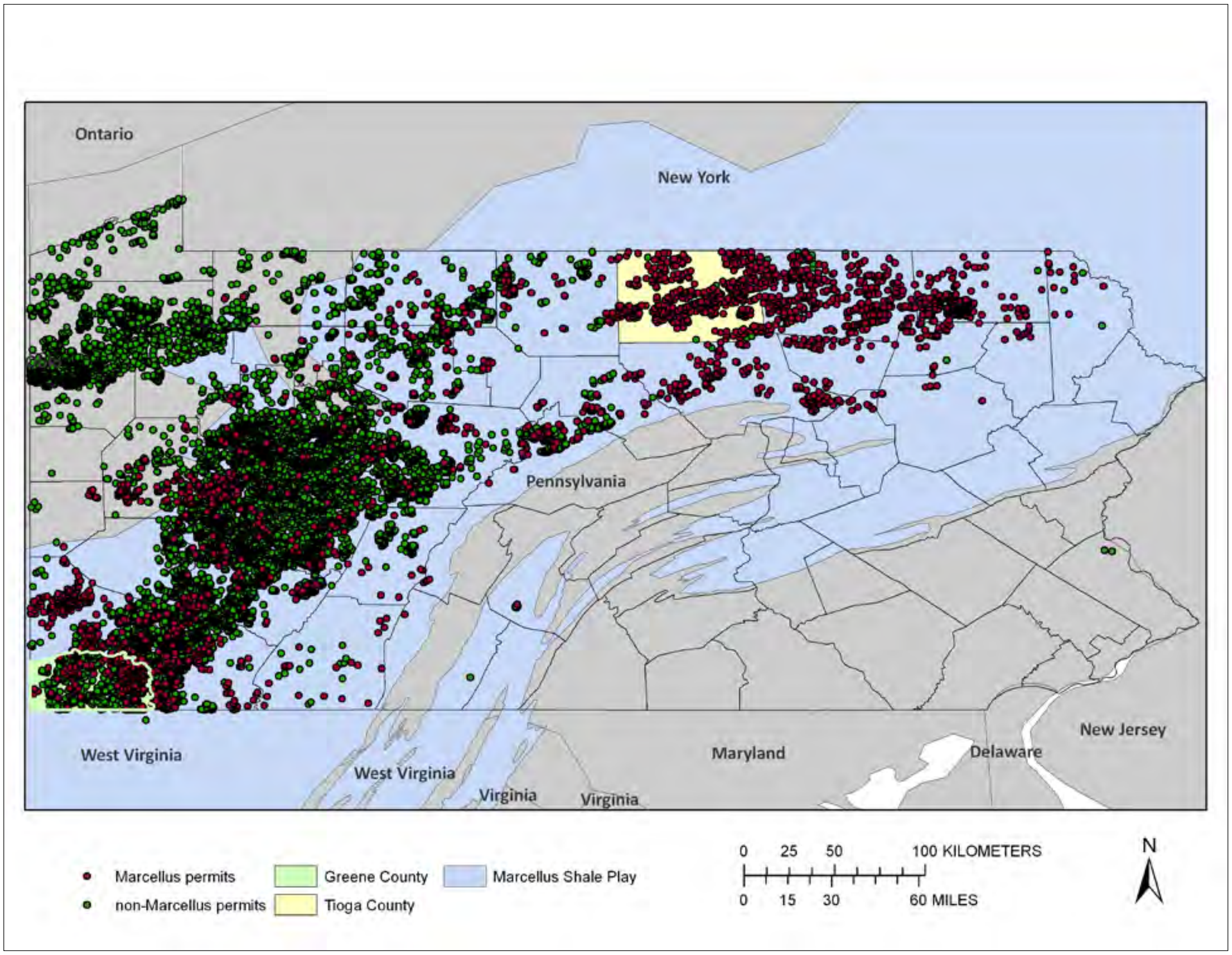

**Figure 3**. The distribution of Marcellus and non-Marcellus natural gas permits issued between 2004 and 2010 within Pennsylvania, the focal counties of Greene and Tioga, and their relation to the Marcellus Shale Play Interior assessment unit. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*)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

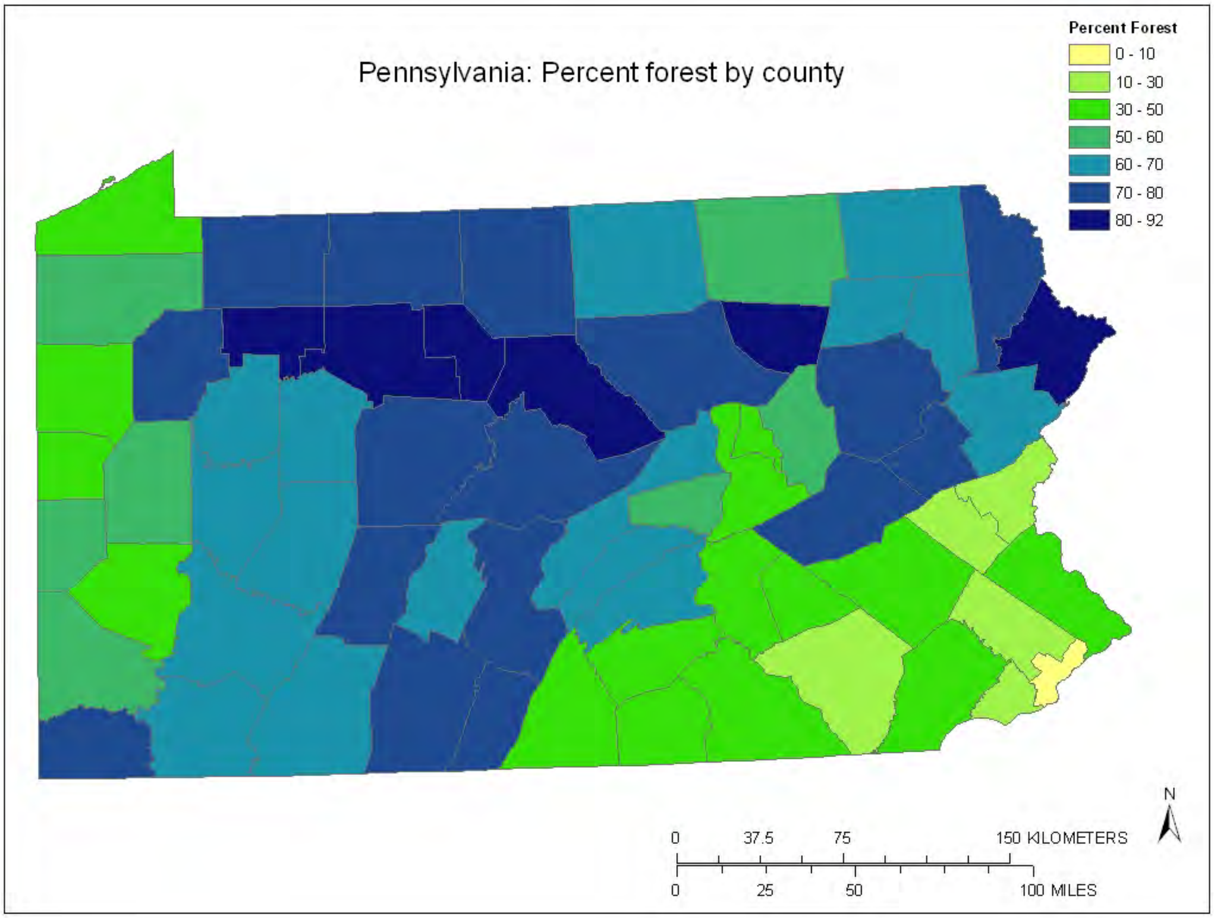

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Data. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

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.

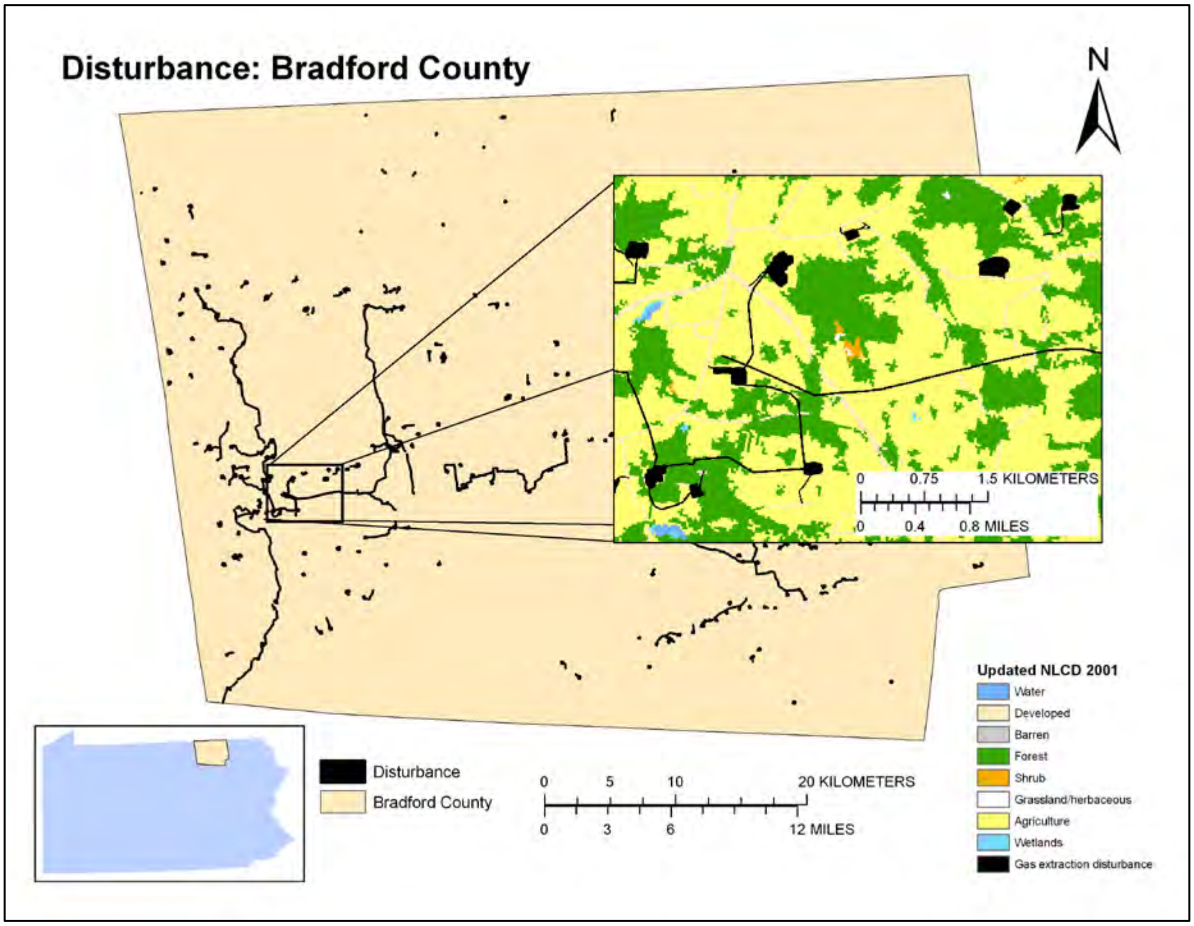

**Figure 5.** Example of the natural gas disturbance footprint of Bradford County, Pennsylvania, embedded within the National Land Cover Dataset (NLCD) 2001. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## 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.

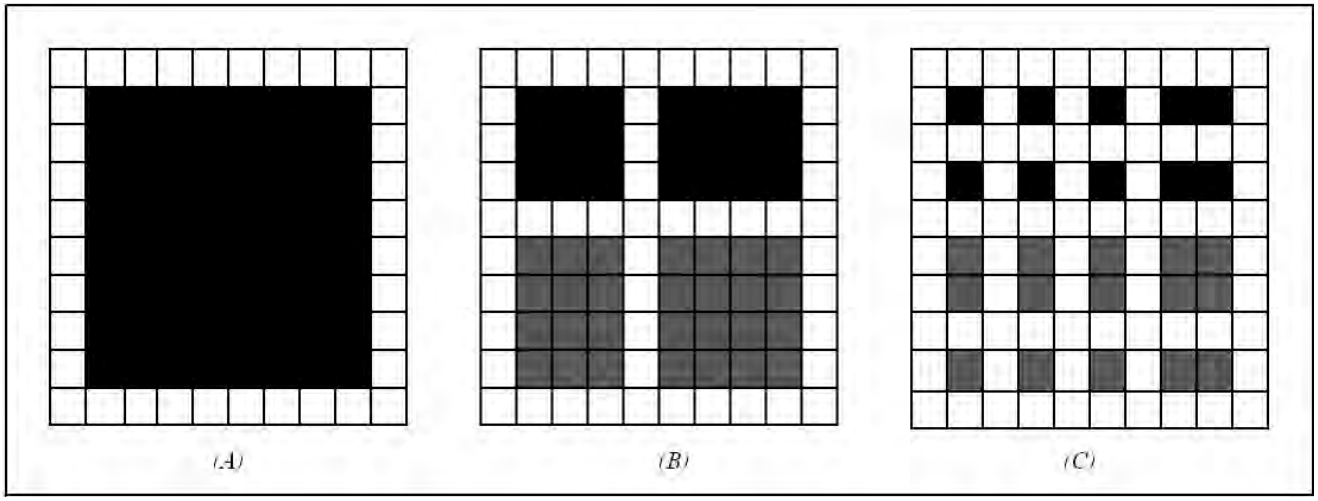

**Figure 6.** Conceptual illustration of interior forest and how critical habitat is affected by linear disturbance. (*A*) High interior area, (*B*) Moderate interior area, and (*C*) Low interior area (Riitters and others, 1996).

## 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).

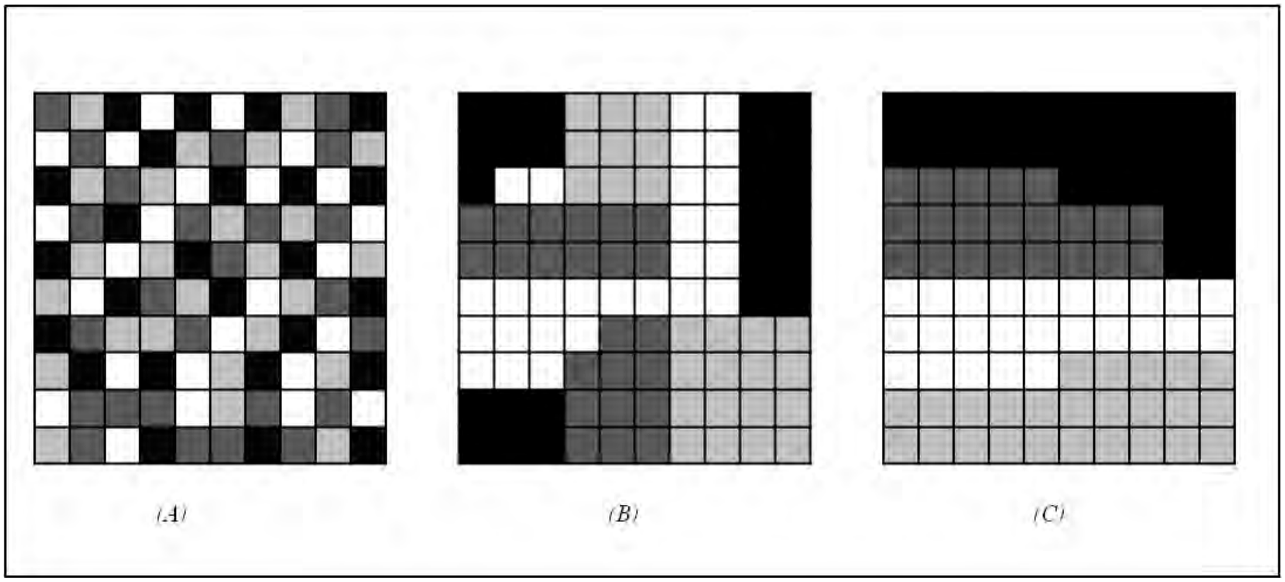

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or "clumped" to one another. *(A)* Low contagion, *(B)* Moderate contagion, and *(C)* High contagion (after Riitters and others, 1996).

## 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 | |

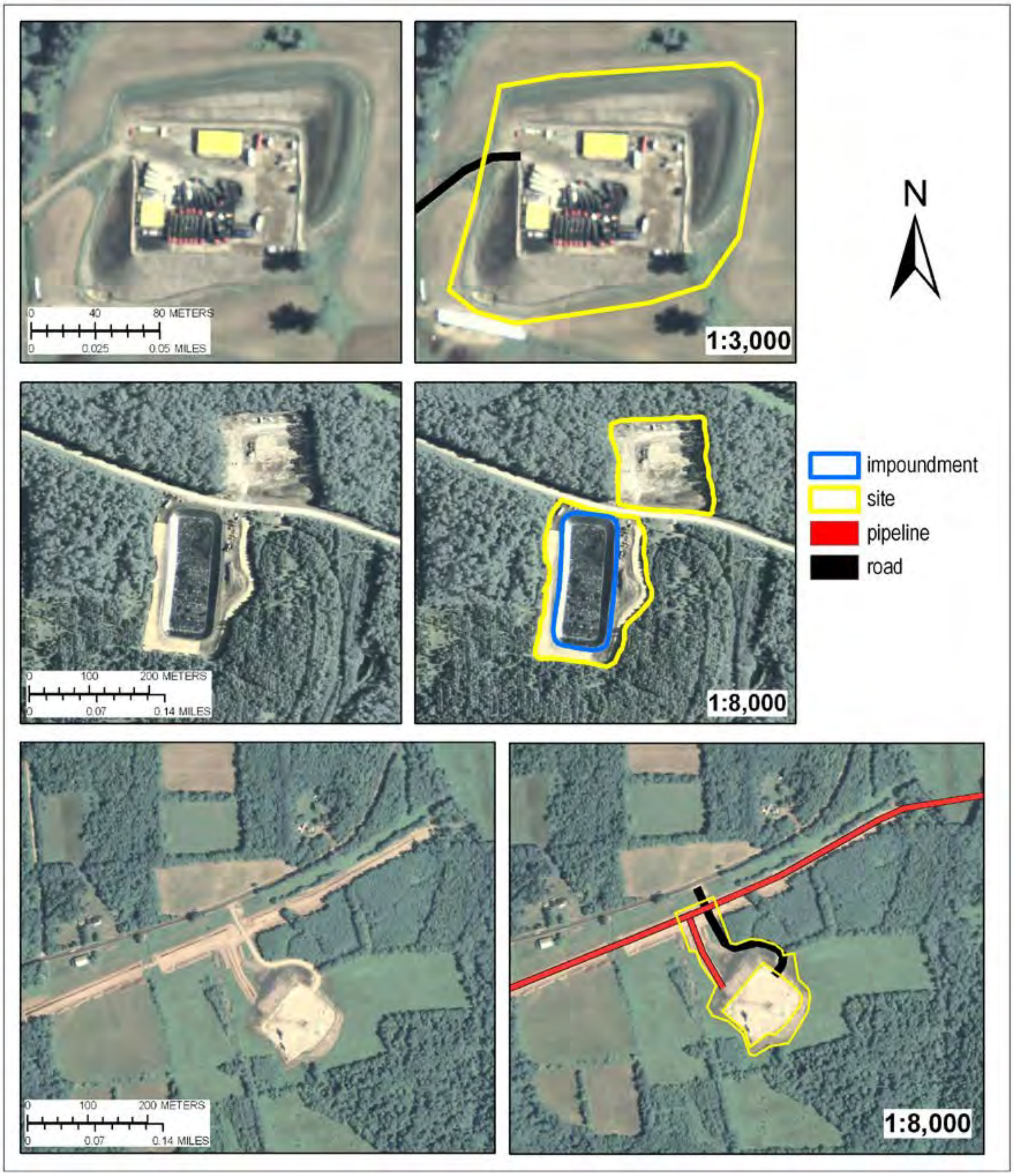

**Figure 8.** Examples of spatially explicit features of disturbance that were extracted from aerial photos into a geographic information systems (GIS) format.

## 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.).

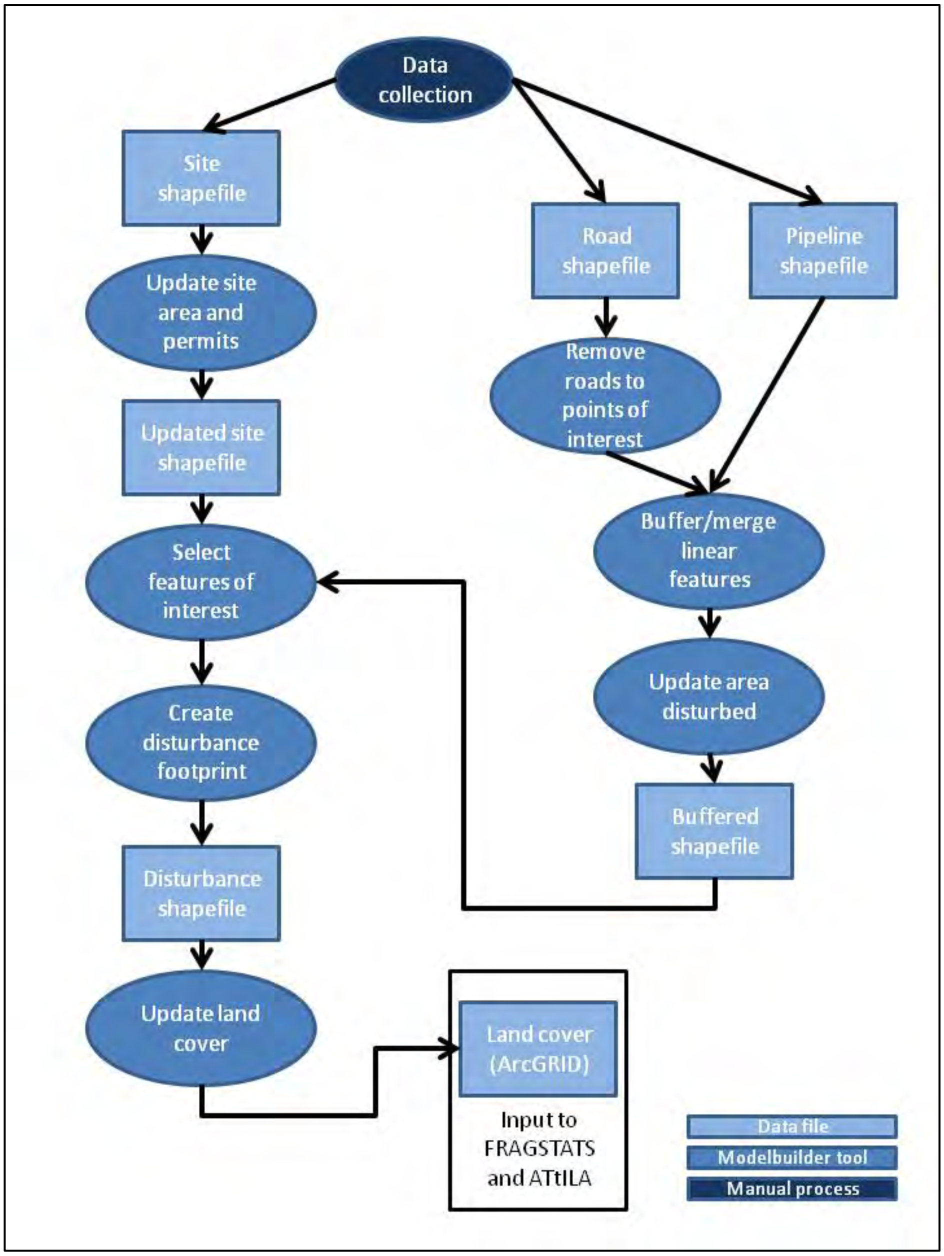

**Figure 9.** Workflow diagram for creating an updated land cover map. The workflow is implemented using ArcGIS model builder automated scripts to process the digitized data and embed in the resampled NLCD 2001.

## 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.

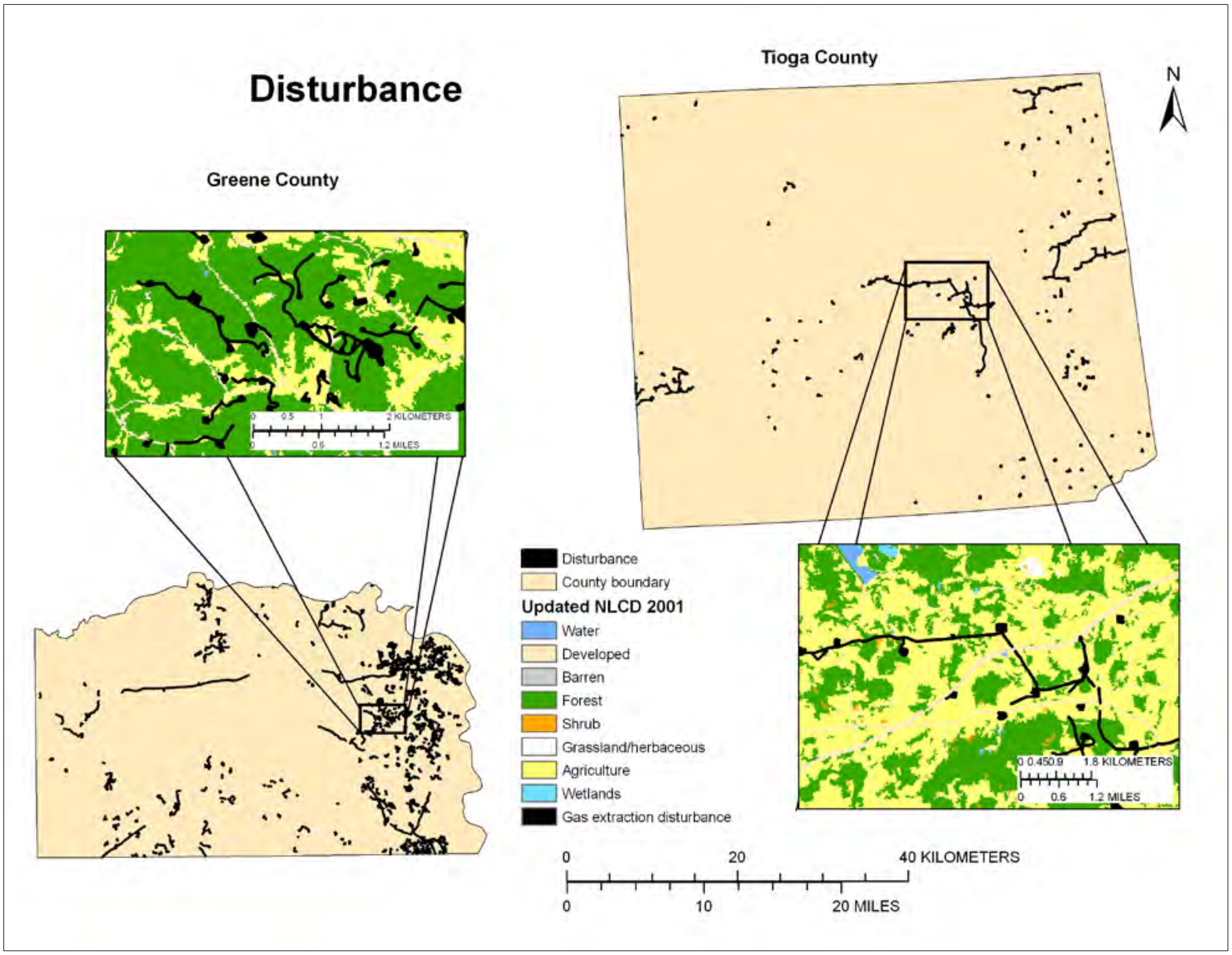

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Greene and Tioga Counties, Pennsylvania. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

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.

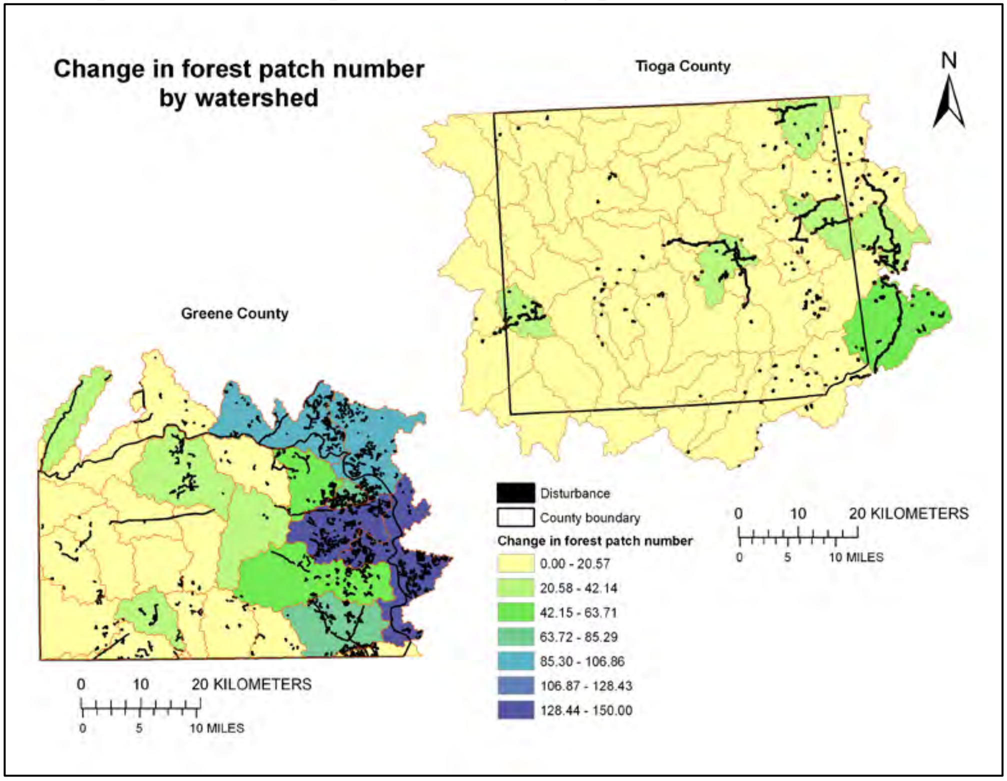

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing the increasing fragmentation in Green and Tioga Counties, Pennsylvania. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## 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 |

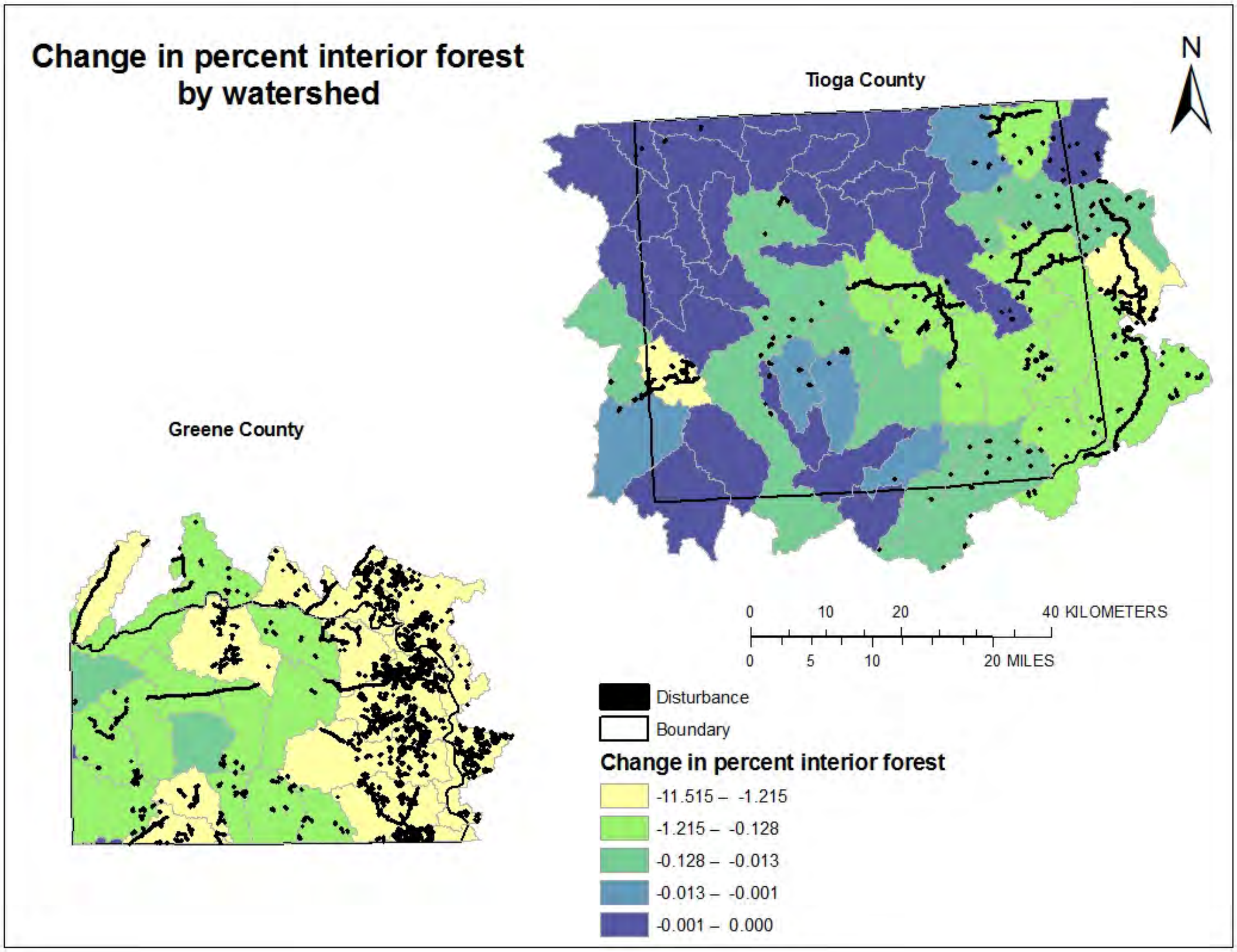

**Figure 12.** Change in percent interior forest in Greene and Tioga Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

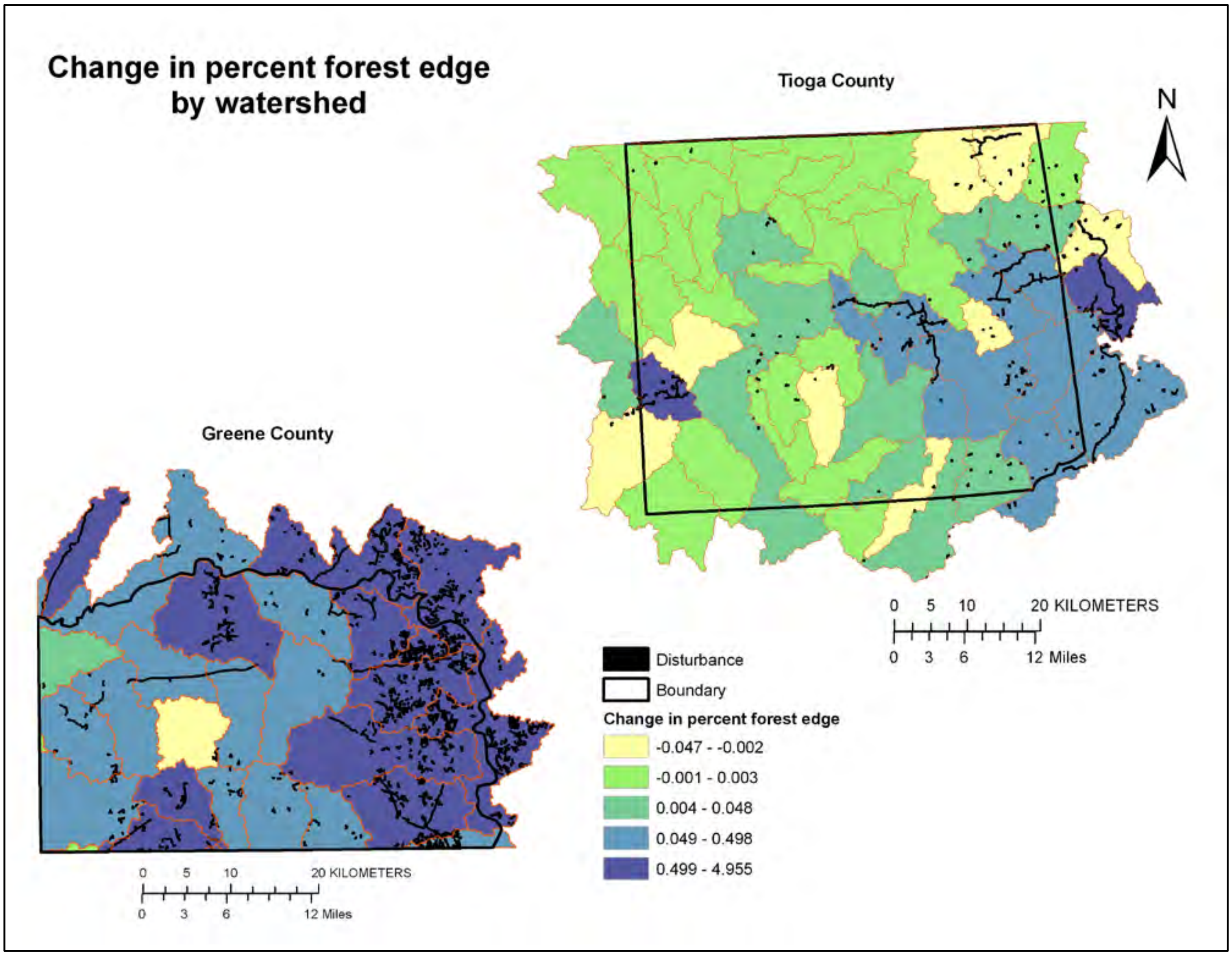

**Figure 13.** Change in percent of edge forest in Greene and Tioga Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Map [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## 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).

# 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

## 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.

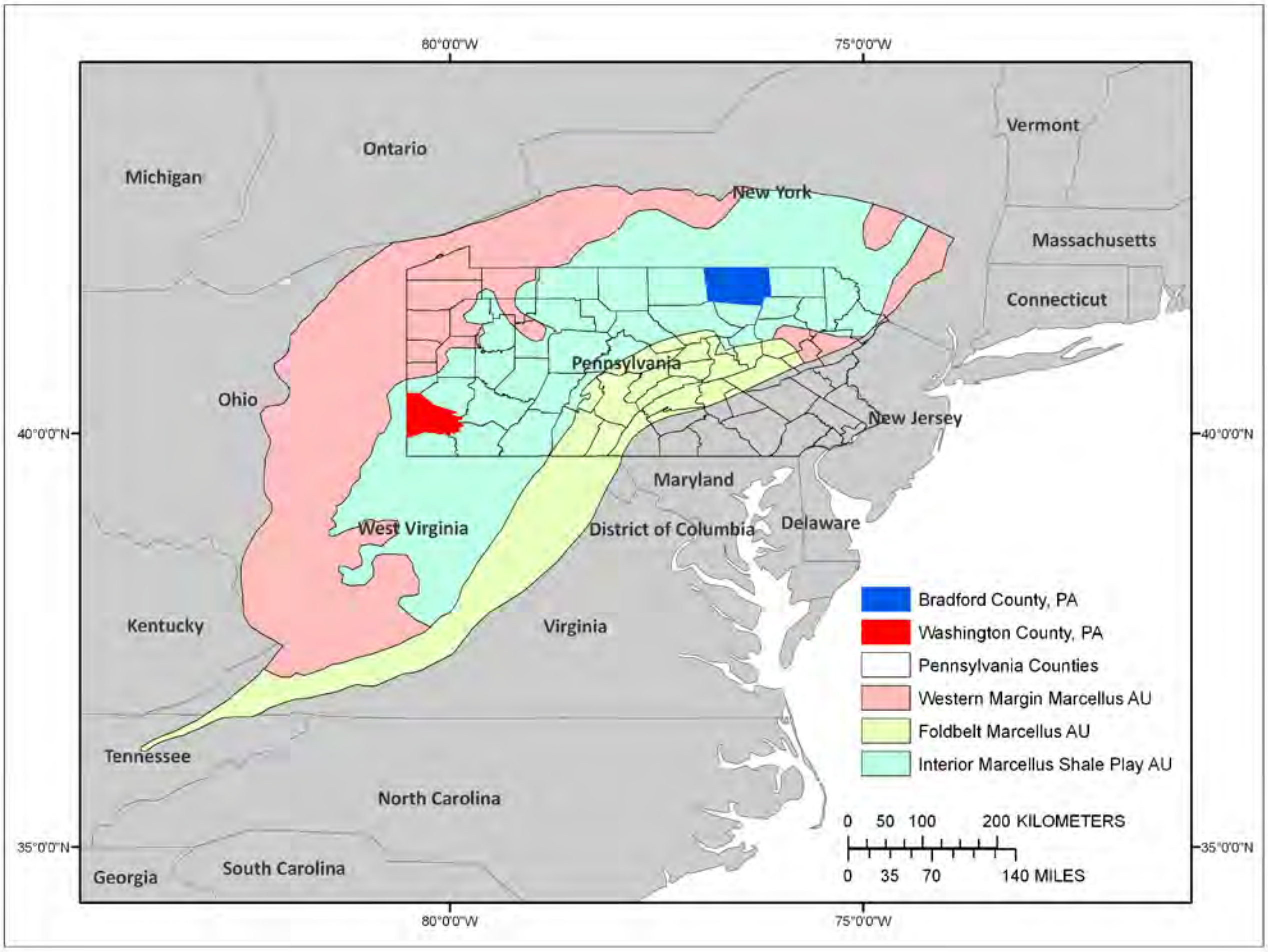

**Figure 1.** Map of the Appalachian Basin Province showing the three Marcellus Shale assessment units (AU), which encompass the extent of the Middle Devonian from its zero-isopach edge in the west to its erosional truncation within the Appalachian fold and thrust belt in the east. The Interior Marcellus 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.

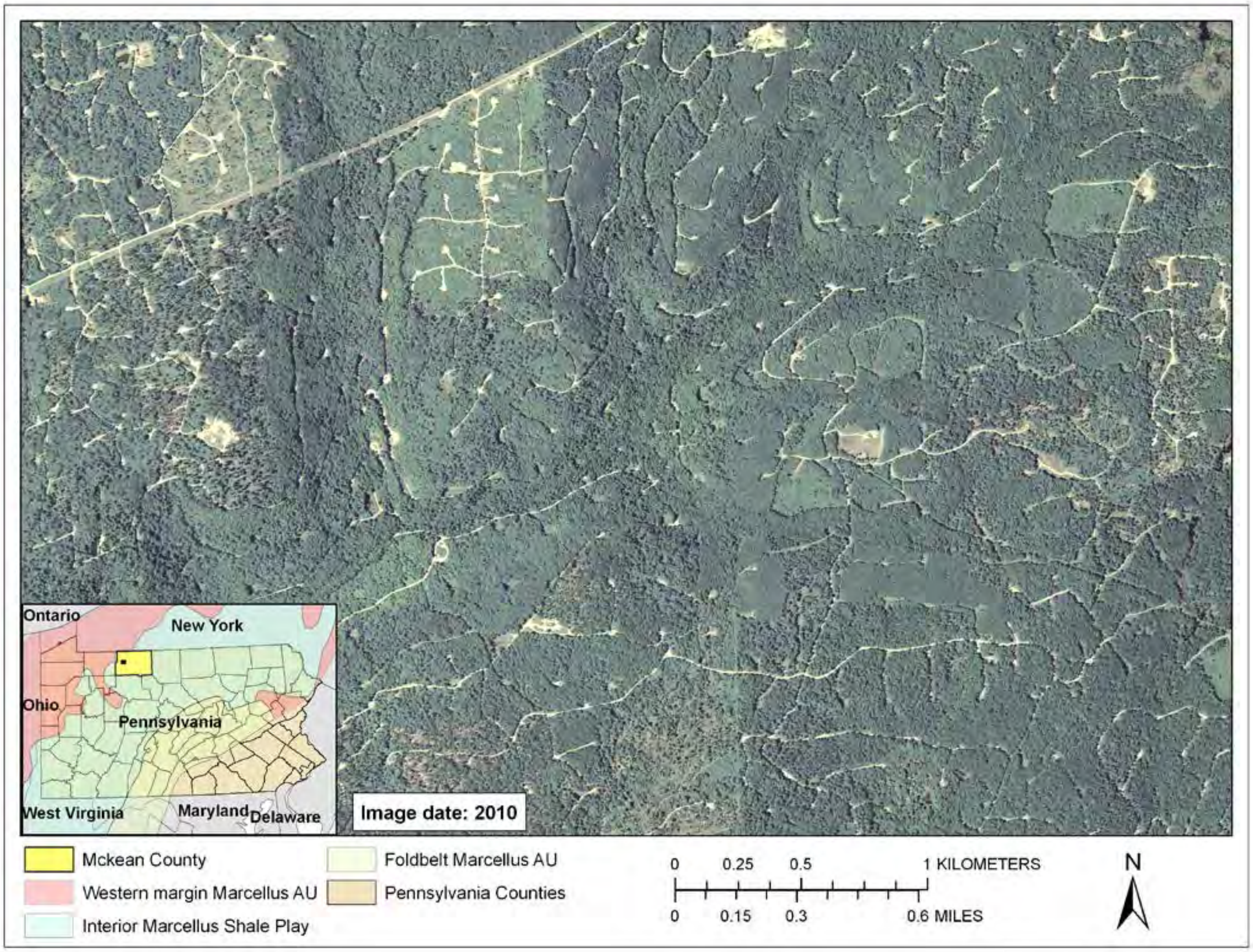

**Figure 2.** A forested landscape in McKean County, Pennsylvania, showing the spatial effects of roads, well pads, and pipelines related to natural gas development. Inset shows the location of the image. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological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

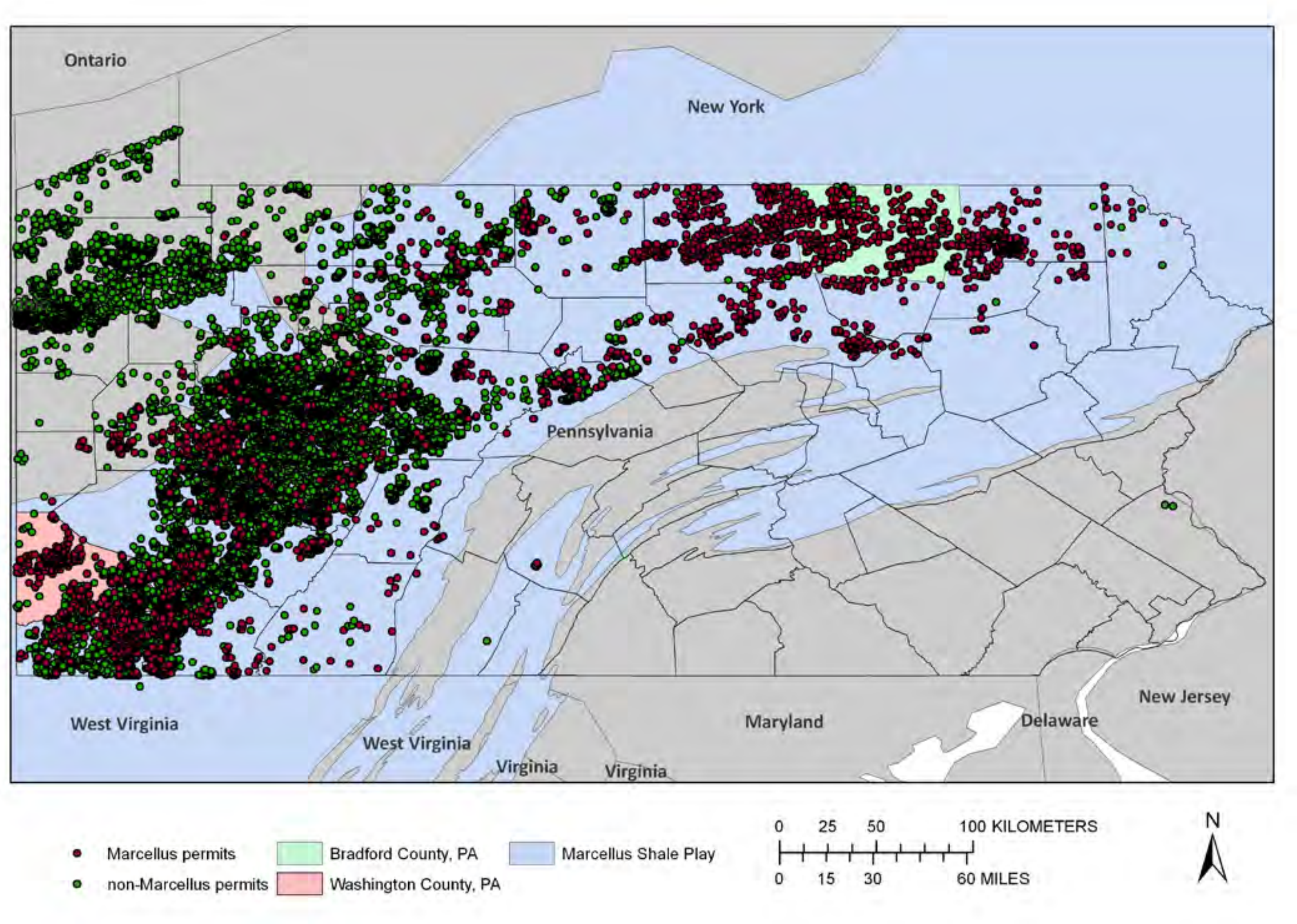

**Figure 3.** The distribution of Marcellus and non-Marcellus natural gas permits within Pennsylvania, the focal counties of Bradford and Washington, and their relation to the Marcellus Shale Play Interior assessment unit. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*)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

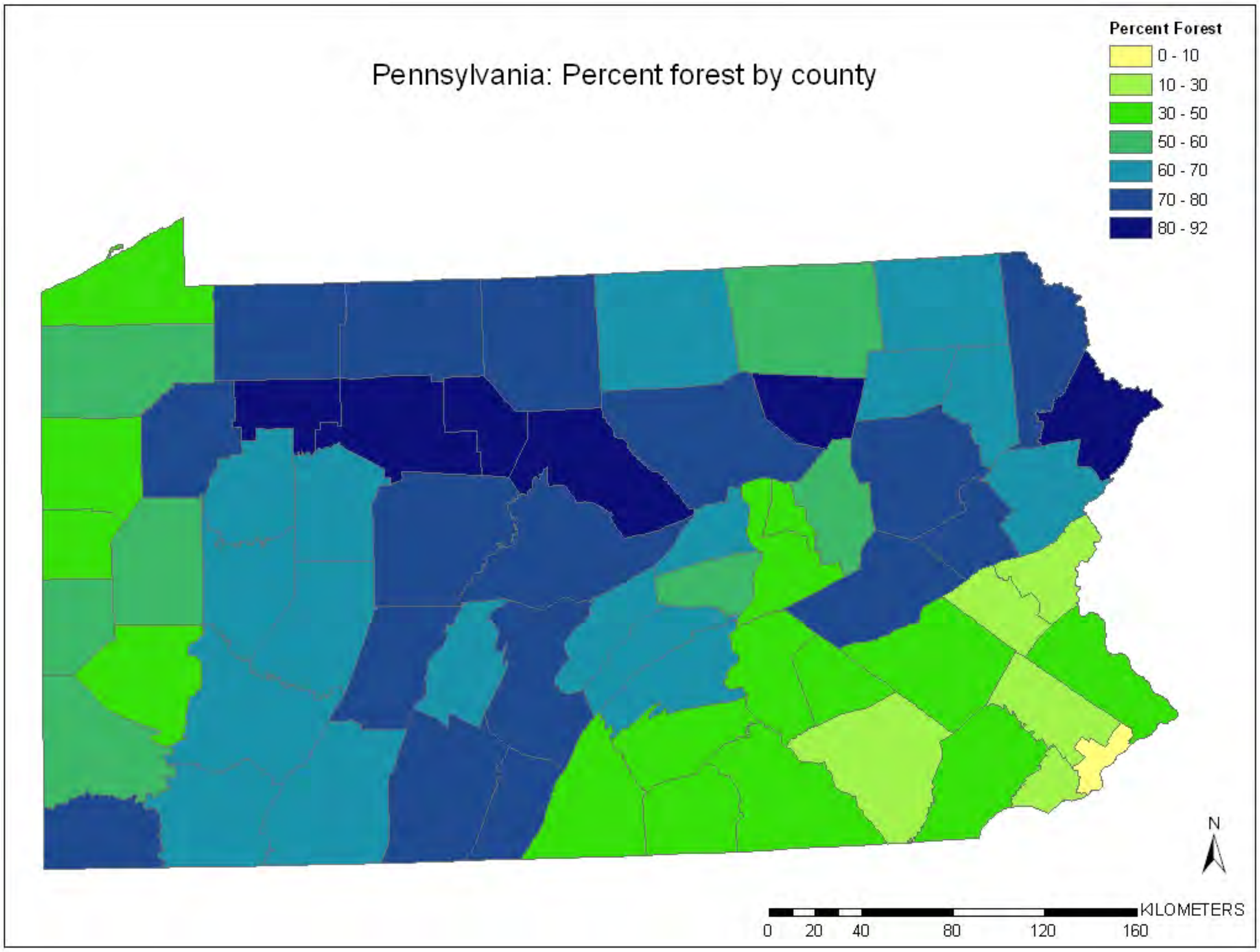

**Figure 4.** The distribution of percent forest cover by county based on the U.S. Geological Survey 2001 National Land Cover Data. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

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.

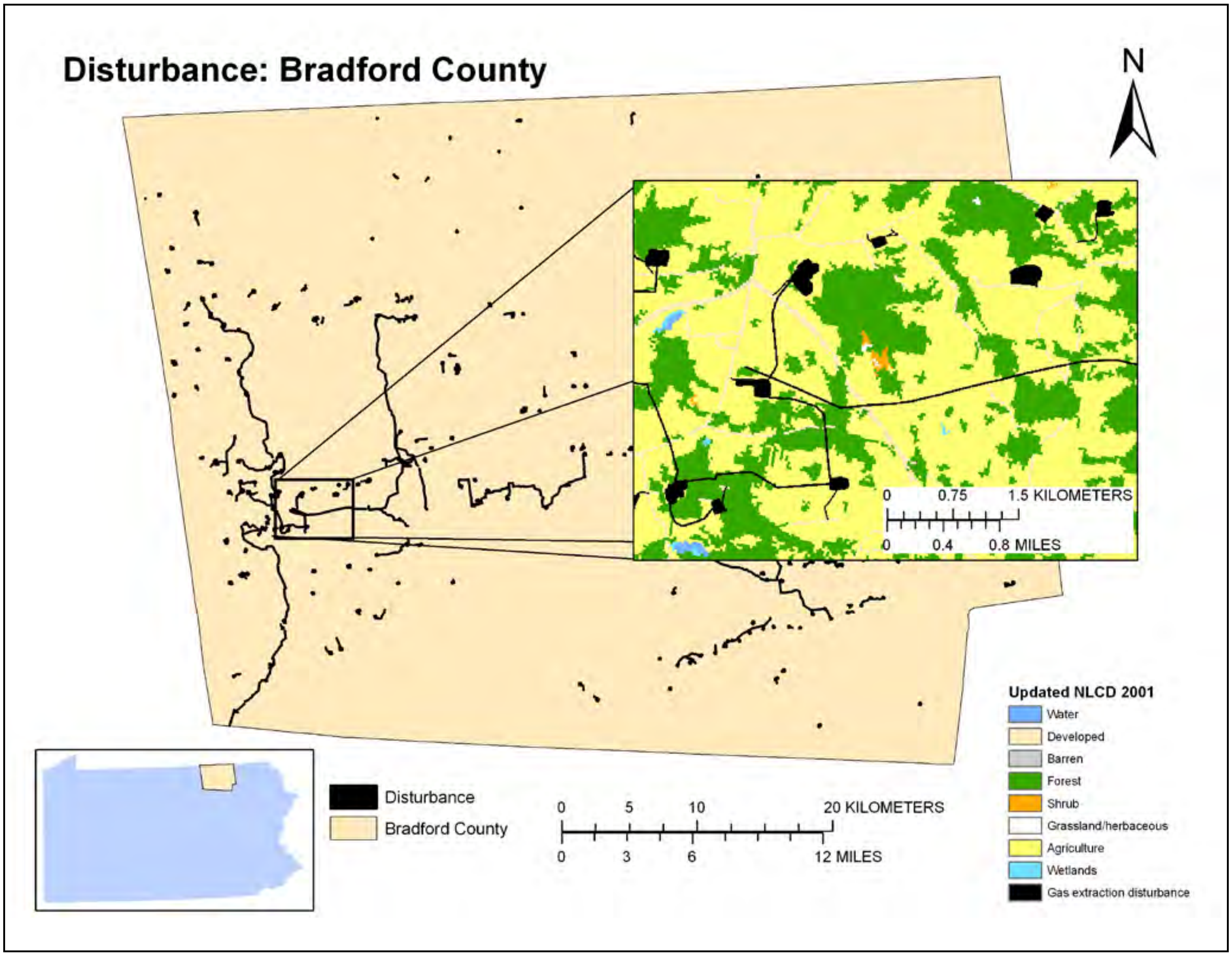

**Figure 5.** The natural gas disturbance footprint of Bradford County, Pennsylvania, embedded within the National Land Cover Dataset (NLCD) 2001. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## 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.

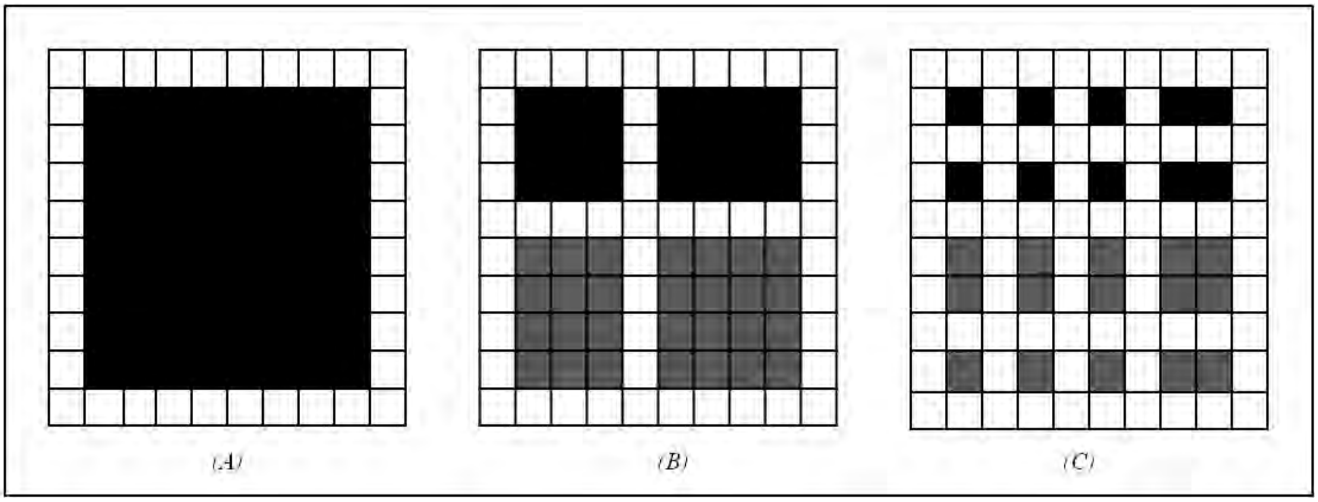

**Figure 6.** Conceptual illustration of interior forest and how this critical habitat is affected by linear disturbance. (*A*) High interior area, (*B*) Moderate interior area, and (*C*) Low interior area (Riitters and others, 1996).

## 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).

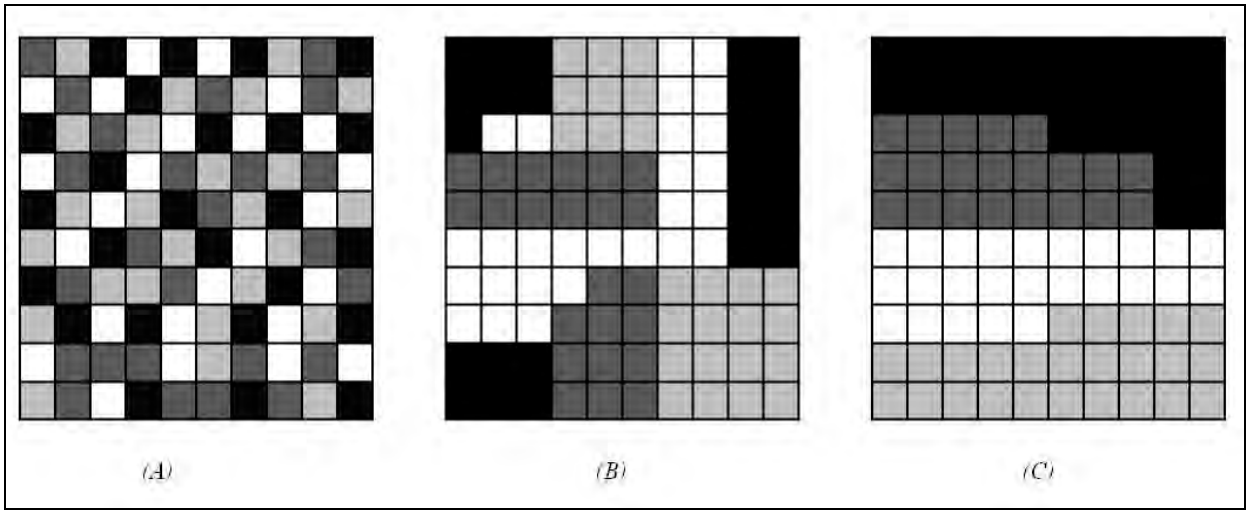

**Figure 7.** The concept of contagion is the degree to which similar land cover pixels are adjacent or "clumped" to one another. (*A*) Low contagion, (*B*) Moderate contagion, and (*C*) High contagion (Riitters and others 1996).

### 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.

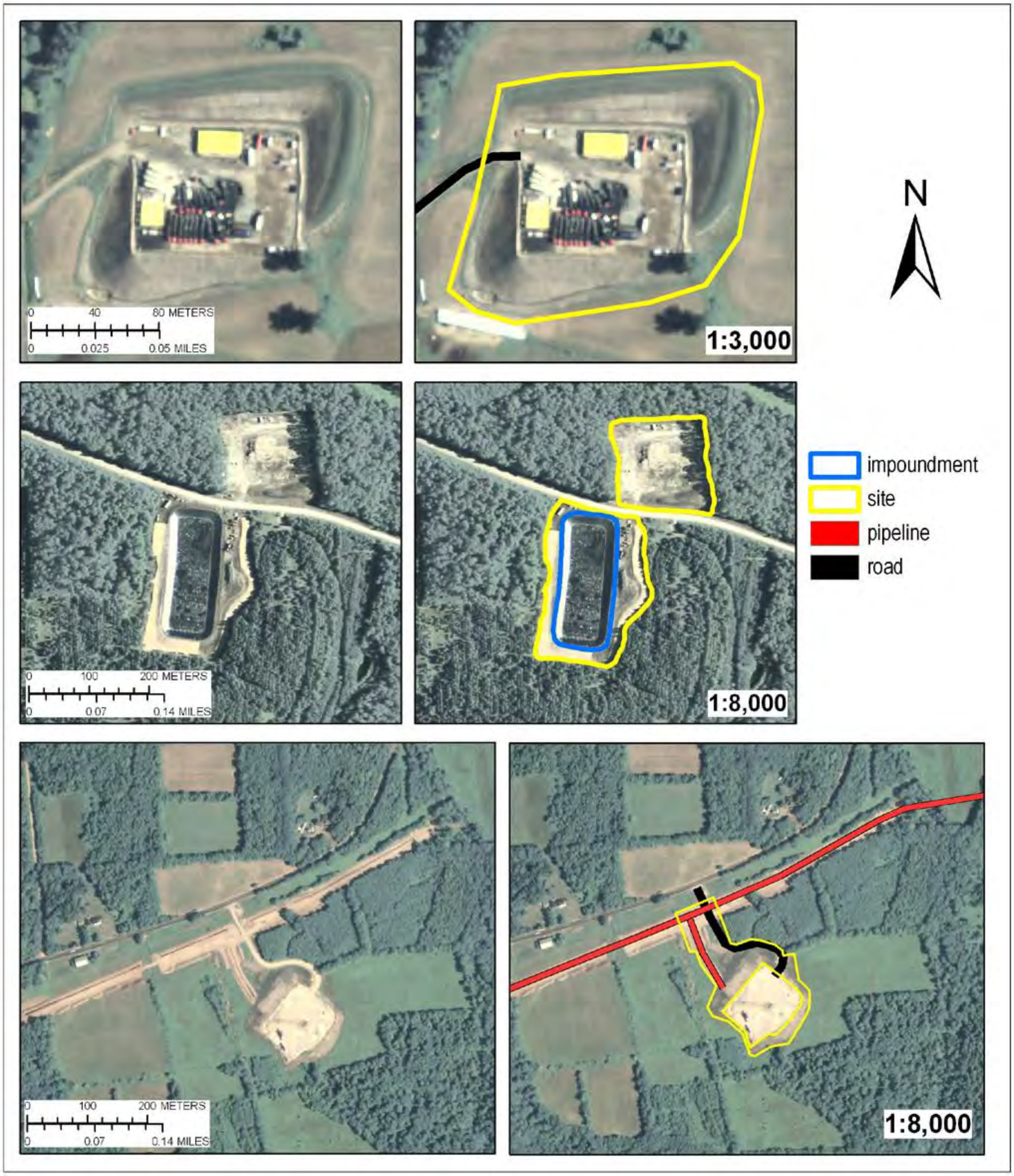

**Figure 8.** Examples of spatially explicit features of disturbance that are being extracted from aerial photos into a geographic information systems (GIS) format.

## 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.).

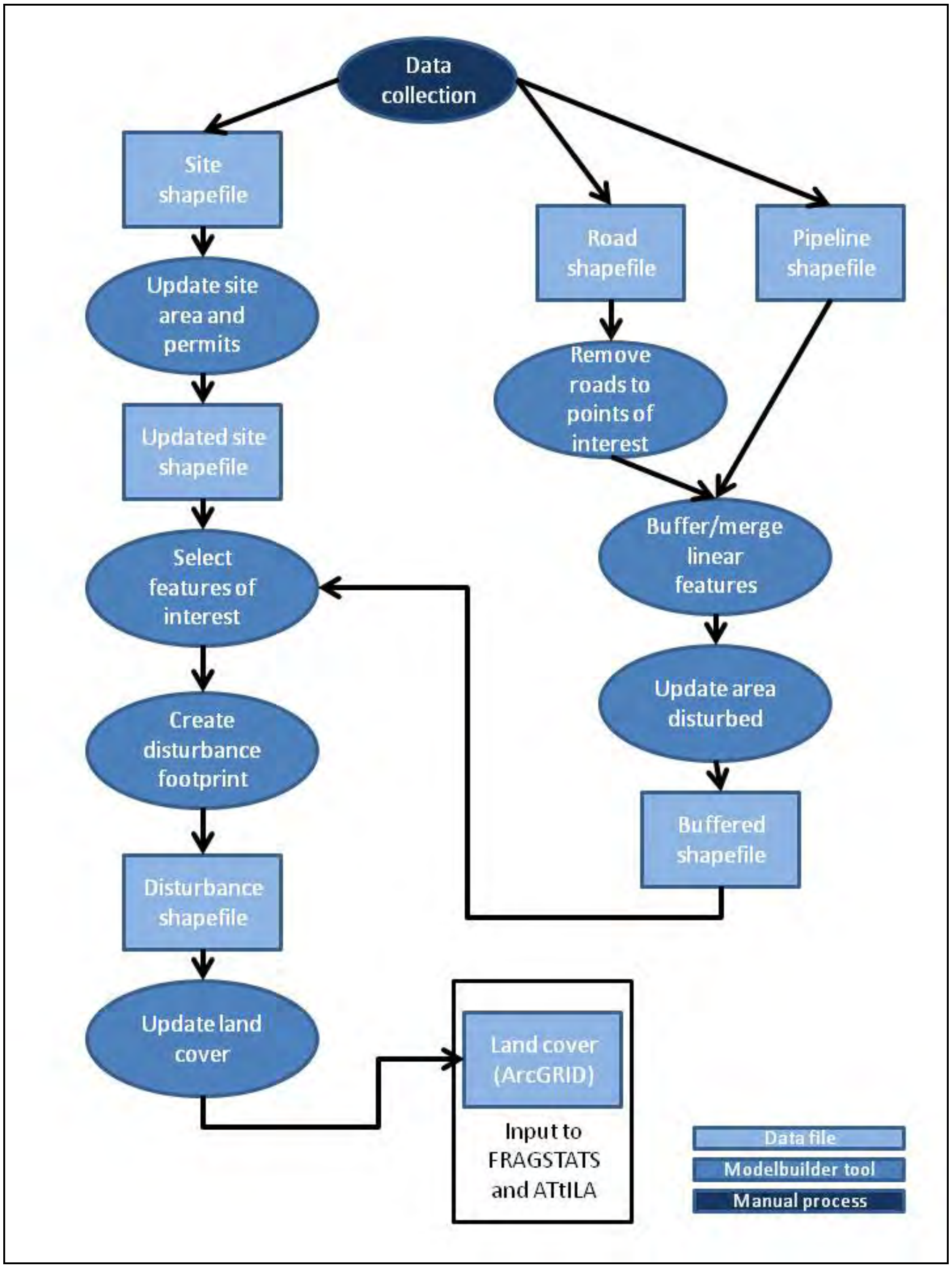

**Figure 9.** Workflow diagram for creating an updated land cover map.

## 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.

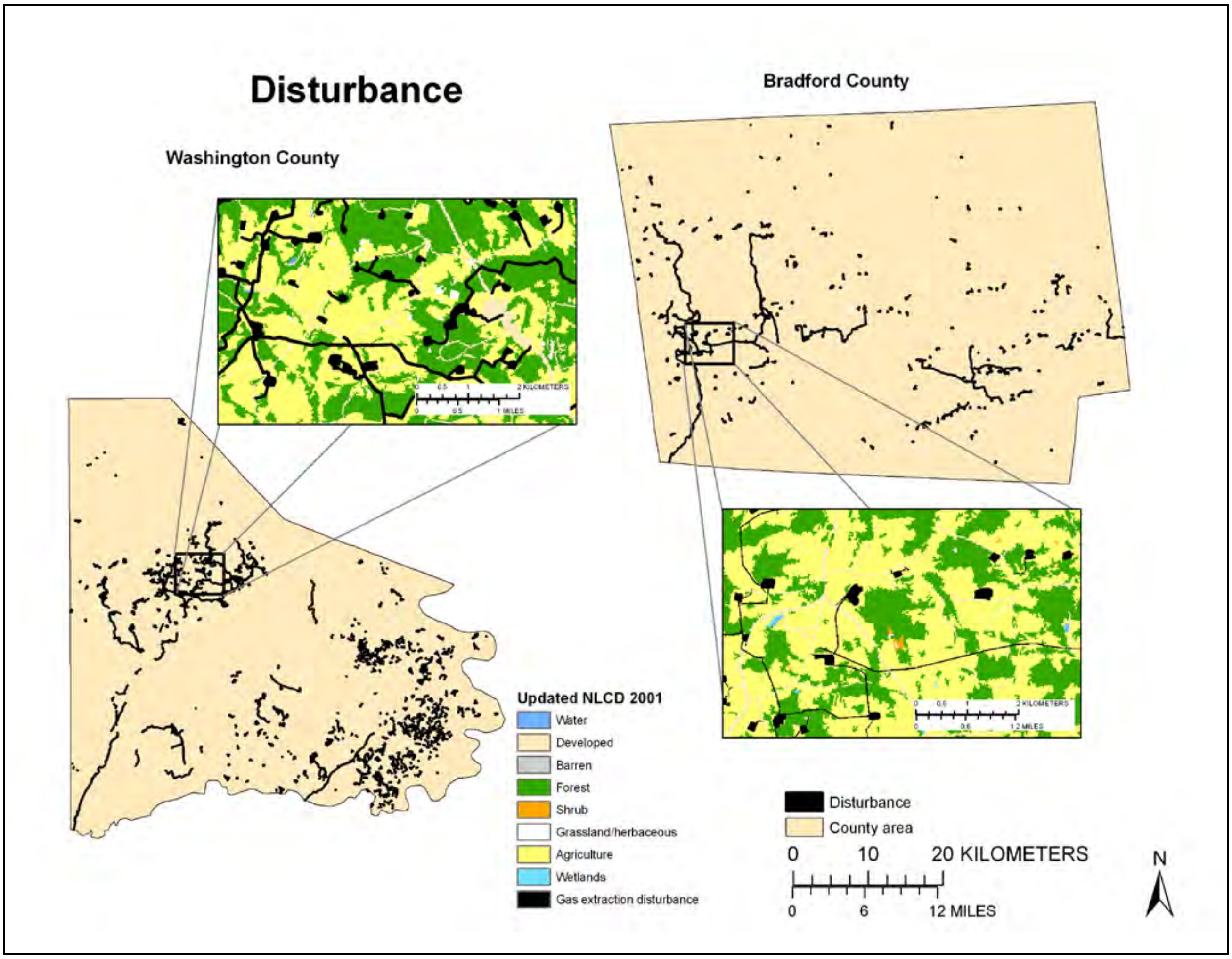

**Figure 10.** Gas extraction-related disturbance identified between 2004 and 2010 in Bradford and Washington Counties, Pennsylvania. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

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.

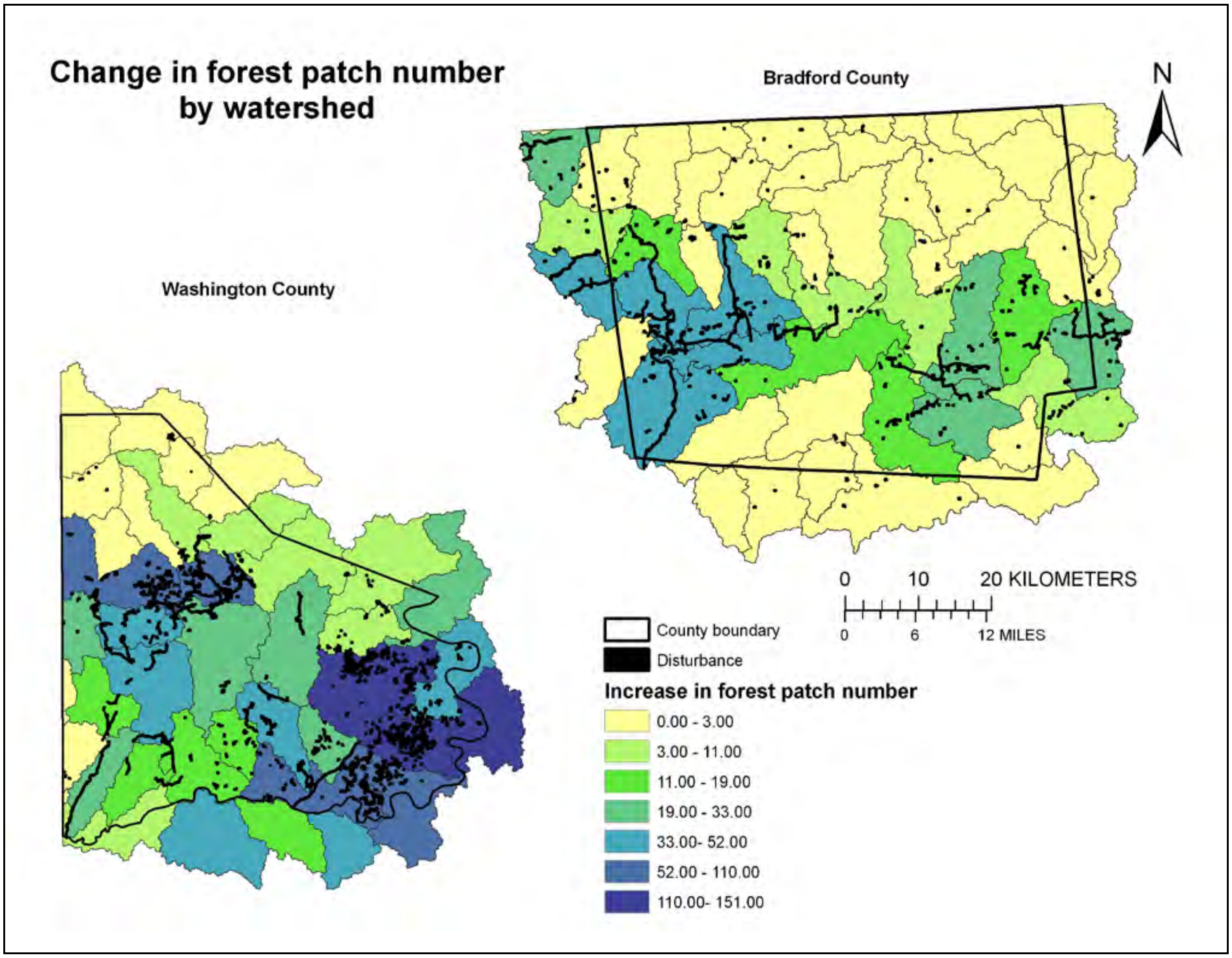

**Figure 11.** Change in number of forest patches from 2001 to 2010 showing increasing fragmentation in Bradford and Washington Counties, Pennsylvania. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## 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 |

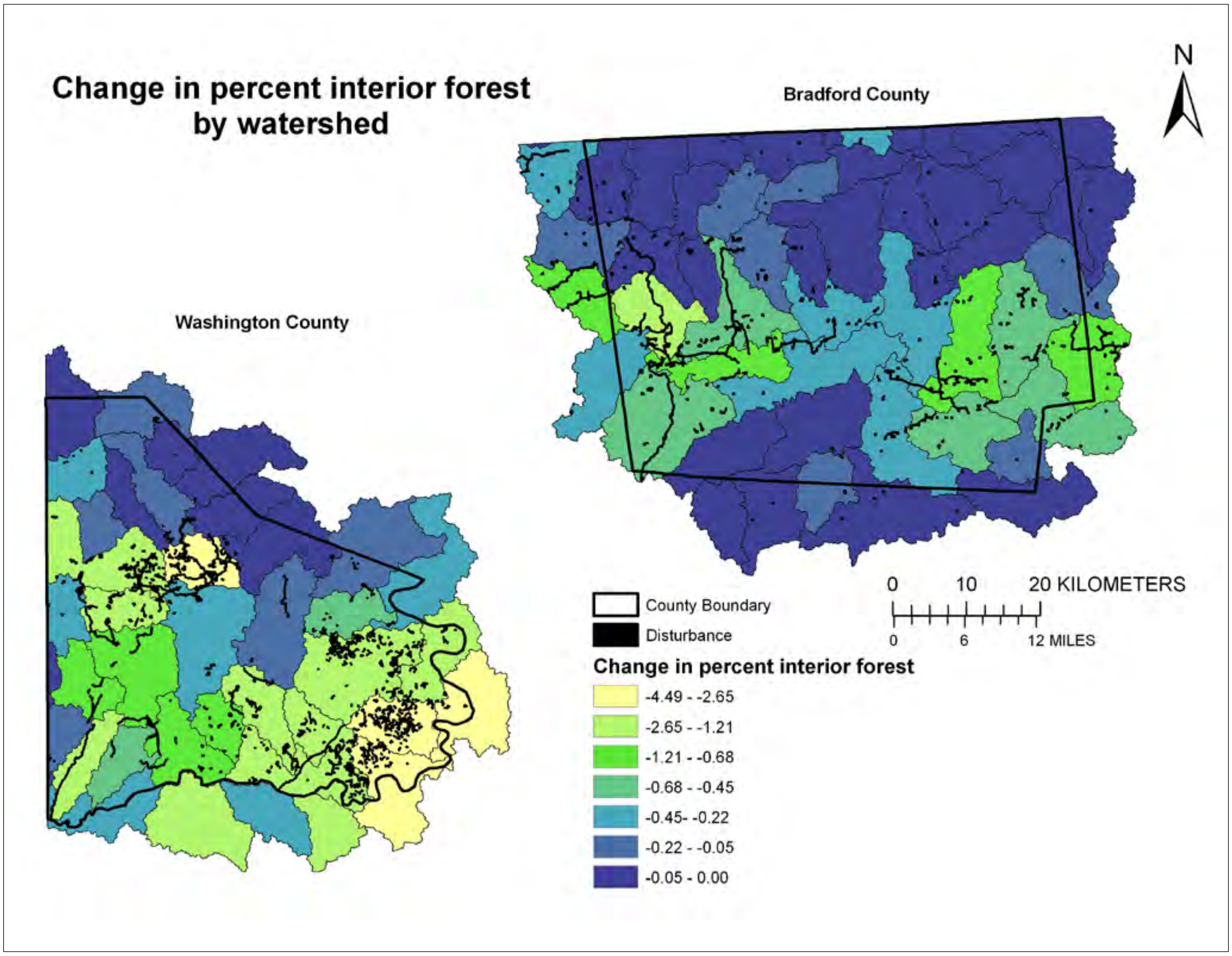

**Figure 12.** Change in percent interior forest by watershed in Bradford and Washington Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Atlas [(*http://viewer.nationalmap.gov/viewer*) (U.S. Geological Survey, 2011)].

## 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.

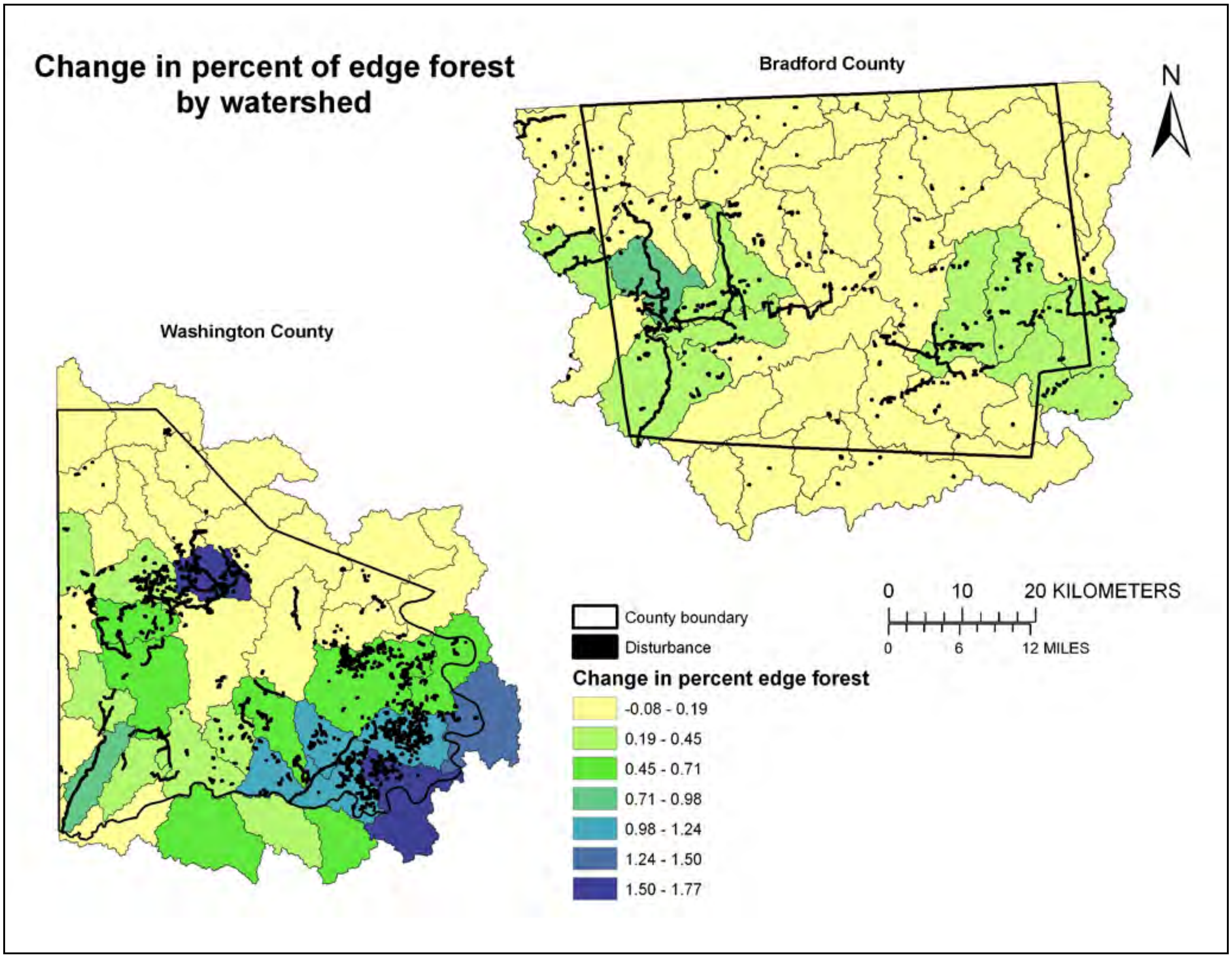

**Figure 13.** Change in percent of edge forest by watershed in Bradford and Washington Counties, Pennsylvania, from 2001 to 2010. Base-map data courtesy of the National Atlas [(http://viewer.nationalmap.gov/viewer) (U.S. Geological Survey, 2011)].

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