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ENVIRONMENTAL ASSESSMENT

Early Trends in Landcover Change and Forest Fragmentation Due to Shale-Gas Development in Pennsylvania: A Potential Outcome for the Northcentral Appalachians

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Abstract Worldwide shale-gas development has the potential to cause substantial landscape disturbance. The northeastern U.S., specifically the Allegheny Plateau in Pennsylvania, West Virginia, Ohio, and Kentucky, is experiencing rapid exploration. Using Pennsylvania as a proxy for regional development across the Plateau, we examine land cover change due to shale-gas exploration, with emphasis on forest fragmentation. Pennsylvania's shale-gas development is greatest on private land, and is dominated by pads with 1–2 wells; less than 10 % of pads have five wells or more. Approximately 45–62 % of pads occur on agricultural land and 38–54 % in forest land (many in core forest on private land). Development of permits granted as of June 3, 2011, would convert at least 644–1072 ha of agricultural land and 536–894 ha of forest land. Agricultural land conversion suggests that drilling is somewhat competing with food production. Accounting for existing pads and development of all permits would result in at least 649 km of new road, which, along with pipelines, would fragment forest cover. The Susquehanna River basin (feeding the Chesapeake Bay), is most developed, with 885 pads (26 % in core forest); permit data suggests the basin will experience continued heavy development. The intensity of core forest disturbance, where many headwater streams occur, suggests that such streams should become a focus of aquatic monitoring. Given the intense development on private lands, we believe a regional strategy is needed to help guide infrastructure development, so that habitat loss, farmland conversion, and the risk to waterways are better managed.

Keywords Shale-gas · Gas · Marcellus · Fragmentation · Core forest · Disturbance

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Introduction

Given widespread shale-gas development in the United States (USGS 2011), Canada (Campbell and Horne 2011), and Europe (Chevron 2011; Haliburton 2011; Stuart 2011), understanding more specifically how landscapes are physically changing due to this resource extraction, and what challenges might persist with reclamation, is paramount. Specifically to the northeastern U.S., rapid development of natural gas from shale formations (most notably the Marcellus) (Engelder and Lash 2008) could substantially increase landscape disturbance across the Allegheny Plateau in Pennsylvania, West Virginia, Ohio, and Kentucky. Across Pennsylvania (Fig. 1), shale-gas development is occurring in forested areas (Ritters and others 2002; Wickham and others 2010), and could result in the loss of core forest due to forest fragmentation (Johnson 2010). Further development on state forests is likely to alter the ecological integrity and wild character of state forests (PADCNR 2011a). These concerns are supported by research on forest fragmentation (Robinson and others 1995; Fahring 2003) and by landscape fragmentation resulting from oil and gas development in other North

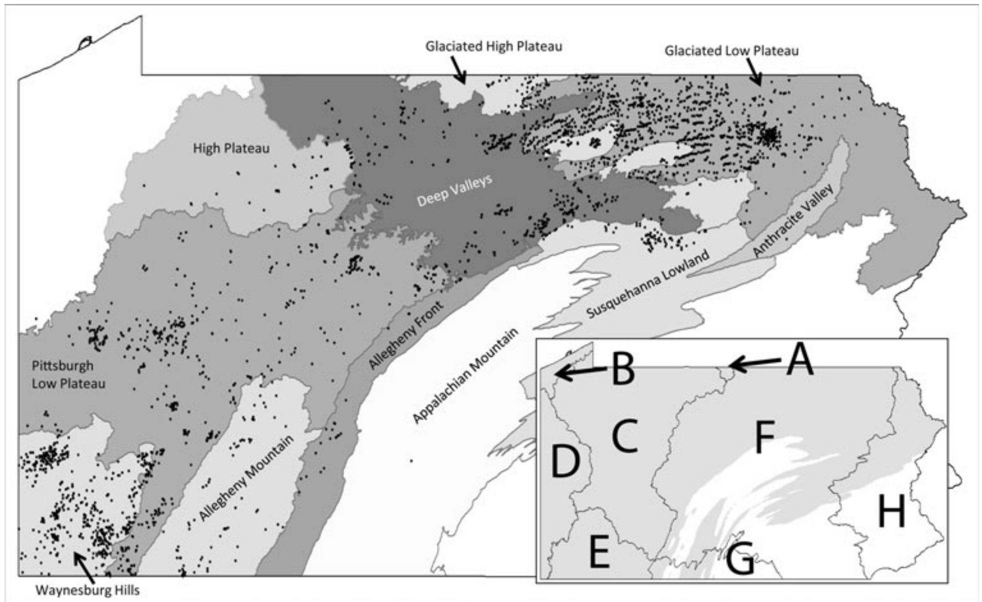

Fig. 1 *Black dots* on main map indicate Pennsylvania pad locations (existing and permitted) across physiographic sections. *Inset* map shows in *gray* the extent of the Marcellus shale formation, and in outline, the state's major hydrologic basins: (*A*) Genesee; (*B*) Erie; (*C*) Allegheny; (*D*) Ohio; (*E*) Monongahela; (*F*) Susquehanna; (*G*) Potomac; (*H*) Delaware

American habitat types (Machtans 2006; Holloran and others 2010; Moseley and others 2010; Gilbert and Chalfoun 2011).

Although some work has been conducted in the western United States on natural gas development and landscape effects, little has been published to date in the eastern United States. Forest covers 6.3 million ha (~61 %) of Pennsylvania (USFS 2011) and is widespread across the Allegheny Plateau (Rosenberg 2003; Sayler 2011) and surrounding states (Heilman and others 2002). Northern Pennsylvania's active shale-gas development (Fig. 1) is occurring in an area of substantial core forest (Ritters and others 2002; Wickham and others 2010), which serves as a habitat reserve for many species (Rich and others 2004; Brittingham and Goodrich 2010; Steele and others 2010; PADCNR 2011a, b), and provides protection for exceptional-value, headwater streams (1st-order streams) (Nadeau and Rains 2007). These streams contribute to major river systems, such as the Susquehanna, which drains into Chesapeake Bay (Lowrance and others 1997). Given that shale-gas development is active across the Allegheny Plateau of several surrounding states (West Virginia, Kentucky, and Ohio), or is expected to be (New York), Pennsylvania's experience can provide an important perspective on current and potential landscape change in the region.

More than 325,000 oil and gas wells have been drilled in Pennsylvania since 1859 (PADEP 2011b). Shale-gas development has been active in Pennsylvania since 2004, and as of June 3, 2011, a total of 2,931 wells had been drilled in the state (PADEP 2011c). Although shallow gas wells still far outnumber shale-gas wells in the region underlain by Marcellus shale, shale-gas drilling is far deeper, and the spatial footprint of the well pad is typically greater. Shale-gas pads are typically 1.2–2 ha (Johnson 2010; PADEP 2011a) but are potentially larger (~12 ha with disturbance other than the pad included (Johnson 2010)), whereas 1 ha or less disturbance is typical for a shallow well (USDA-ANF 2007). Drilling-related land disturbance occurs due to road development or expansion of existing roads; drill pad and associated stormwater system development; gathering-line placement to move extracted gas to main transmission lines; compressor station development to pump gas to transmission lines; freshwater storage pond creation for hydraulic fracturing (also known as fracing); flowback water storage ponds and treatment facilities; and development of staging areas for equipment storage.

Therefore, our primary objective was to investigate how Pennsylvania's landscapes are changing in response to shale-gas exploration, with specific emphasis on land cover change patterns and the increased occurrence of forest fragmentation in the Allegheny Plateau, Northcentral Appalachians (the area of the Marcellus formation). Our working hypothesis is that shale-gas development is occurring largely in forest cover (given its wide extent across the Marcellus shale region) and resulting in greater fragmentation, especially of core forest.

We first examine pad development effects on land cover change across public versus private land, and across physiographic regions and major hydrologic basins. Second, we examine whether shale-gas development in forested areas is resulting in forest fragmentation, especially in core forest where headwater stream systems are common

(Nadeau and Rains 2007). This knowledge is used to identify regional trends of landscape change, which can be used to help guide shale-gas infrastructure development, minimize forest fragmentation, and advance long-term monitoring of development in the region.

Research Methods

Gas Development and Land Ownership

We limited our analysis to Pennsylvania because its gas well database and GIS data sets are accessible and its landscapes are similar to surrounding states where drilling is occurring (Ohio and West Virginia) or possible (New York). Given that pad extents are not tracked by state or federal government, we used well location data for drilled and permitted wells for the dates up to and including June 3, 2011 (PADEP 2011b) (Fig. 1). Using ArcGIS 9.3 (ESRI 2011), we identified wells associated with a pad, and the pad center point, by creating a 50 m buffer around all wells, dissolving the overlapping buffers, and determining the center point of each remaining polygon (the calculated pad center). We used 2010 USDA National Agriculture Imagery Program (NAIP) imagery (USDA-NAIP 2011) with existing pads to cross check 25% of pads with photography and found the ArcGIS method to accurately capture wells with pads; however the database evolves with updates and our calculation should be considered an estimate of numbers of pads. To compare patterns and differences in gas development between existing and permitted pads, we identified permitted pads as those for which a permit had been granted but on which no wells had been drilled by June 3, 2011 (no spud date (representing the initiation of drilling) in the DEP database); permits prior to 2007 were excluded. We identified existing pads as those with a spud date for at least one well on or prior to June 3, 2011. Existing pads give a snapshot of current conditions, whereas permitted pads give a view of future conditions. Therefore, depending on our specific research question, we used either the pad center or well location for GIS data extraction.

We sought to compare pad development trends in relation to other pads, roads, and streams, and across major hydrologic basins and physiographic sections of the state. We used our calculated pad center point for existing and permitted pads to determine the pad's occurrence within a major hydrologic basin (PGDC 2011a) and physiographic section (PAGS 2011), and to calculate minimum distance of a pad to the nearest stream (PGDC 2011b) and unpaved ((PGDC 2011c) and paved (PGDC 2011d, e) road.

To determine if pad development differed between private and public land (Pennsylvania state game land, state forest, and national forest), we identified the public land ownership class using our calculated pad center point and 2009 Pennsylvania state game land (PGDC 2011f), state forest (PGDC 2011g), and Allegheny National Forest surface ownership (USDA-ANF 2011) data. In Pennsylvania, mineral rights can be held by private individuals while the surface is in public ownership. We could not identify private ownership of mineral rights given our methodology. Consequently, some of the pads on public land may have been in private mineral rights ownership (PADEP 2011c). Although mineral right ownership can substantially affect infrastructure development during lease negotiations, examination of differences in gas development on public and private land may yield valuable information on landscape trends.

Land Cover

To determine the land cover at developed or potential sites, we used well locations, because they were more accurate than pad locations. We used two methods to determine the land cover for existing and permitted well locations prior to gas development. Our first method (called PAMAP 2005) extracted land cover for each well using the PAMAP program 2005 data (PGDC 2011h), which classifies land cover per the Anderson Land Use/Land Cover system (Anderson and others 1976; PGDC 2011h). Because this data set encompasses land cover classes for the entire state, it was used to identify forest cover for forest fragmentation analysis. However, because it was from ~2005 and was at a 30 m scale, we also used a second data set. Our second method (called USDA NAIP) involved a GIS analyst using 2010 USDA NAIP photography (USDA-NAIP 2011) and well points exported into Google Earth (using its historic aerial photography service) to visually determine land cover. We used simplified land cover classes of forest, agriculture, and disturbed. Agriculture areas consist of row crop or pasture; disturbed areas include strip mine, scrub/shrub, barren, or developed land; and forest areas comprise all forest cover and areas where the well location bordered within 15 m both an agricultural and forested area. In this last case, the forest cover class was used instead of agriculture due to our decision to recognize the loss of a forest cover as a more ecosystem-sensitive habitat conversion (Smail and Lewis 2009). The USDA NAIP method more accurately reflects land cover prior to development, because it uses recently available imagery to determine land cover well locations, and because land cover is directly interpreted for each well location rather than via image classification at a 30 m resolution (as with the PAMAP 2005 data). However, it is not possible, using only this data set, to derive a statewide estimate of forest cover for forest fragmentation analysis, so it was necessary to also use the PAMAP 2005 method.

Forest Fragmentation

Forest cover (deciduous, evergreen, mixed deciduous and evergreen forest, and forested wetlands) data for all of Pennsylvania were extracted from the PAMAP 2005 land cover data (PGDC 2011h). Given the age of this data set, and the temporal period of nearly all shale-gas development, we assumed that this data represents land cover prior to resource development. Across all existing and permitted wells, we determined the forest fragmentation class per Vogt and others (2007) (third-party ArcGIS Landscape Fragmentation Tool ver. 2.0), and chose a 100 m edge distance for our analysis, given its extensive use to classify edge habitat (Temple 1986; Robbins and others 1989; Goodrich and others 2002; Howell and others 2007; Johnson 2010; Svobodová and others 2011). Our analysis resulted in four forest pattern classes: core forest, perforated forest, edge forest, and patch forest (Vogt and others 2006). Core forest consisted of forested pixels greater than 100 m from non-forested pixels; patch forest consisted of forest pixels that did not contain core forest (forested pixels were not greater than 100 m from non-forested pixels); edge and perforated classes also contained forest pixels within 100 m of a non-forest class, however, edge forest occurred along the outside edge of a core forest area, while perforated forest was adjacent to the interior edge of a core forest area. A value for each pad was derived by (i) using the well value (if one well per pad), or (ii) using the majority forest fragmentation class of all wells on a pad (if more than one well per pad).

Statistical Analysis

Counts of existing versus permitted pads were used to examine patterns by land cover categories (forest, agriculture, and disturbed) across physiographic sections and major hydrologic basins. A nonparametric two-sample Mood Median test (Minitab Inc. 2003) was used to test for significant differences between existing and permitted pads, and the minimum distance to a road or stream on private and public land by forest fragmentation class, physiographic section, and major hydrologic basin. To determine if the addition of permitted pads to the landscape would result in a significant difference in the minimum distance between pads, we used a Mood Median test with existing pads versus the database of all potential pads. An alpha of 0.05 was used to indicate statistically significant differences, and an alpha of 0.10 was used to identify marginally significant relationships for future study.

Results

Land Cover and Ownership Patterns

Shale gas development has been steadily increasing since 2005 (Fig. 2a). As of June 3, 2011, there were 2,931 wells drilled (3,364 permitted) and 1,465 pads constructed (2,458 pads with existing or permitted wells). The mean and maximum number of wells per pad is increasing each year (Fig. 2a), but more than 75 % of pads have 1–2 wells per pad (Fig. 2b).

USDA NAIP land cover data (year 2010) indicate that 38 % of existing pads occur in forest cover (permitted pads, 45 %) and 62 % in agricultural cover (permitted pads, 54 %) (Table 1a). Permitted pad construction would result in an 81 % increase over existing pads in forest cover and a 60 % increase in agricultural cover. PAMAP 2005 data indicate 54 % of pads occur in forest cover (permitted pads, 57 %) and 45 % in agricultural cover (permitted pads, 43 %) (Fig. 3). The Glaciated Low Plateau has the most existing and permitted pads (Table 1a), followed by the Pittsburgh Low Plateau and Waynesburg Hills sections in the western and southwestern parts of the state, and the Deep Valleys section in the north (Fig. 1).

The Susquehanna River basin has the most existing and permitted pads (60 and 54 %, respectively) followed by the Monongahela, Allegheny, Ohio, and Delaware River basins (Table 1b). The majority of pad development in the Susquehanna River basin is confined to the north in the Glaciated Low Plateau physiographic section (Fig. 1). After the Susquehanna River basin, the Allegheny River

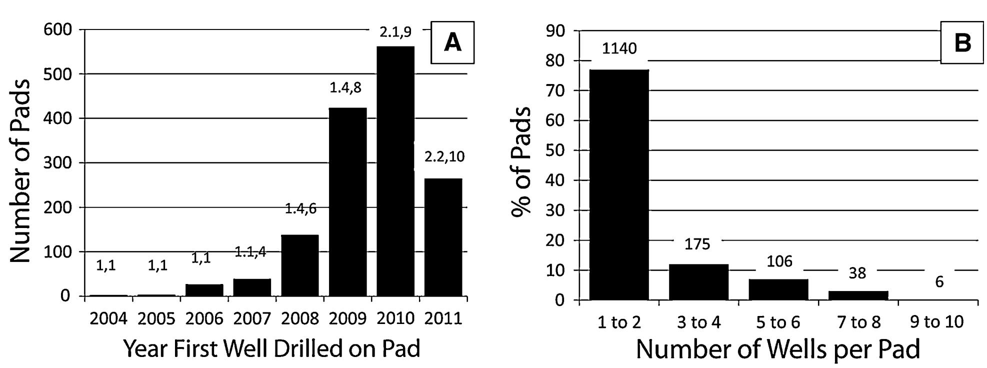

Fig. 2 (**a**) Number of pads built by year. Above each bar is presented the mean wells per pad and maximum wells per pad, respectively (1.1, 4, for example). (**b**) Number of wells per pad as a function of the percentage of all pads. The *number* above a *bar* is the total number of pads in each category

Table 1 Existing and permitted pads and their USDA NAIP interpreted land cover type by (A) physiographic section and (B) hydrologic basin

Physiographic section	Pad N (%)	Land cover		
A.		Forest	Agriculture	Disturbed
Existing				
Allegheny front	10 (<1)	8	2	0
Allegheny mountain	31 (<1)	11	20	0
Anthracite valley	0	0	0	0
Appalachian mountain	0	0	0	0
Deep valleys	161 (11)	112	48	1
Glaciated high plateau	72 (5)	41	31	0
Glaciated low plateau	580 (40)	158	420	2
High plateau	25 (2)	23	2	0
Northwestern glaciated	1 (<1)	0	1	0
Pittsburgh low plateau	273 (19)	106	165	2
Susquehanna lowland	36 (2)	10	26	0
Waynesburg hills	276 (19)	86	190	0
Statewide	1465	555 (38 %)	905 (62 %)	5 (<1 %)
Permitted				
Allegheny front	27(1)	13	1	0
Allegheny mountain	63 (2)	16	27	0
Anthracite valley	1 (<1)	1	0	0
Appalachian mountain	1 (<1)	0	1	0
Deep valleys	538 (16)	101	19	2
Glaciated high plateau	216(6)	20	29	0
Glaciated low plateau	1431 (43)	106	192	2
High plateau	49 (2)	20	1	0
Northwestern glaciated	0 (0)	0	0	0
Pittsburgh low plateau	510(15)	106	122	2
Susquehanna lowland	82 (2)	11	17	0
Waynesburg hills	446(13)	54	130	0
Statewide	993	448 (45 %)	539 (54 %)	6 (<1 %)

Basin	Pad N (%)	Land cover		
B.		Forest	Agriculture	Disturbed
Existing				
Allegheny	199 (14)	97	101	1
Delaware	1 (<1)	0	1	0
Monongahela	259(18)	72	187	0
Ohio	121 (8)	36	85	0
Susquehanna	885 (60)	350	531	4
Statewide	1465	555 (38 %)	905 (62 %)	5 (<1 %)
Permitted				
Allegheny	167(17)	94	71	2
Delaware	3 (<1)	1	2	0
Monongahela	208 (21)	60	148	0
Ohio	82 (8)	24	58	0
Susquehanna	533 (54)	269	260	4
Statewide	993	448 (45 %)	539 (54 %)	6 (<1 %)

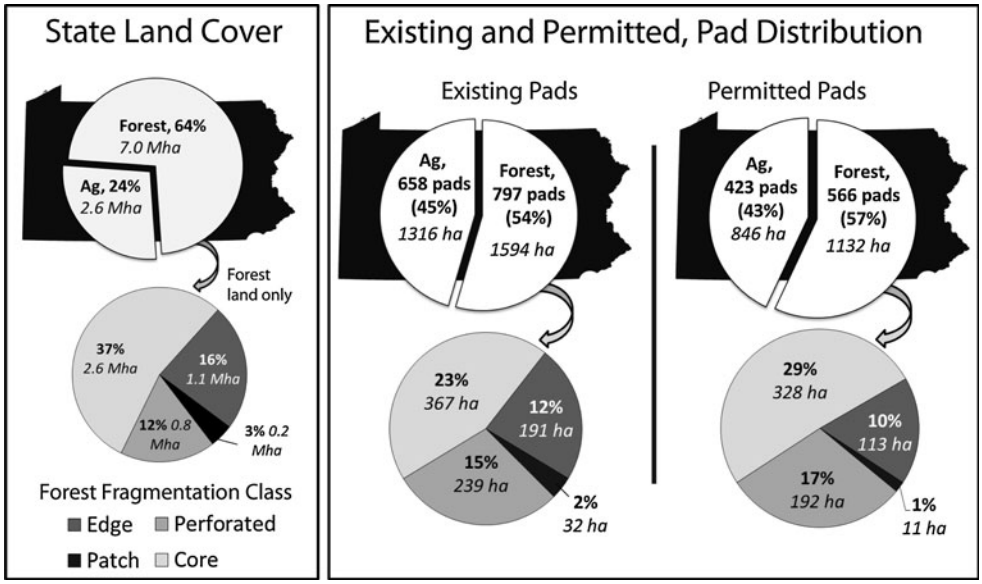

Fig. 3 *Left*. PAMAP 2005 statewide distribution of agriculture (Ag) and forest lands, and forest fragmentation classes. *Mha* million hectares. Right. Distribution of Marcellus existing and permitted pads across PAMAP 2005-derived Ag and forest land cover, and forest fragmentation classes. Hectares converted for each land cover are based on the maximum reported value of 2 ha (pad disturbance ranges from 1.2 to 2.0 ha per pad (Johnson 2010; PADEP 2011a))

basin has the next most existing pads in forest cover followed by the Monongahela and Ohio River basins, respectively. The proportion of permitted pads in forest cover follows a similar trend. Existing pads developed in agricultural cover are greatest in the Susquehanna River basin followed by the Monongahela, Allegheny, and Ohio River basins; the proportion of permitted pads in agricultural cover represents a similar trend. The major drainages affected by shale-gas development in the northcentral and northeast portion of the state would be the west and north branches of the Susquehanna River; Pine Creek; Loyalsock Creek; and the Lackawanna River. In the southwest, the Allegheny, Conemaugh, Ohio, Monongahela, and Youghiogheny drainages are most affected. Across the state's physiographic sections and major hydrologic basins, less than 1% of existing or permitted pads occur in disturbed cover.

Across the state, the minimum distance to a stream is 325 m on both existing and permitted pads, and the minimum distance to a road from an existing (permitted) pad is 247 m (279 m) (Table 2). There was no significant difference between existing and permitted pads in the minimum distance to a road or stream (Table 2). Across major hydrologic basins or across physiographic sections, in the Susquehanna River basin, permitted pads are significantly farther from a pre-existing road than existing pads (Table 3), suggesting that they will require more road construction. Across Pennsylvania, the minimum distance between existing pads is 1,776 m and between all potential pads, 1466 m. The minimum distance between pads was significantly smaller in the Allegheny Mountain, Deep Valleys, and Glaciated Low Plateau physiographic sections for all potential pads versus existing pads; the minimum distance between pads was marginally smaller (alpha = 0.1) in the Pittsburgh Low Plateau, Susquehanna Lowland, and Waynesburg Hills physiographic sections for all potential pads versus existing pads. The minimum distance between pads in the Monongahela and Susquehanna River basins was significantly smaller for all potential pads versus existing pads (Table 3).

Approximately 1,296 (90 %) existing pads are developed on private versus state land (169); permitted pads show a similar trend (Table 4). The majority of public lands with existing or permitted pads are DCNR forest lands. Across public or private land, there was no significant difference in the minimum distance to a stream between existing and permitted pads; however, pads on private lands are farther from roads than pads on public lands (Table 4). On private lands the distance between pads is significantly smaller for all potential pads (1,470 m) than for existing pads (1,806 m). Note that the minimum distance between pads is marginally smaller on public lands for all potential pads (1,439 m) versus existing pads (1,552 m) (alpha = 0.10).

Forest Fragmentation

Across Pennsylvania, 37 % of all forest cover can be classified as core, 16 % as edge, 3 % as patch, and 12 % as perforated (Fig. 3). The percentage of existing pads developed in forest cover is 54 % (45 % agriculture), while the proportion that could be developed by adding in permitted pads is 57 % (agriculture 43 %). Across existing pads, 23 % of pads have been developed in core forest, 12 % in edge, 2 % in patch, and 15 % in perforated. Construction of permitted pads could result in a slight increase in the proportion of core (29 vs 23 % for existing pads) and perforated forest (17 vs 15 % for existing pads) developed.

Table 2 Existing and permitted pad mean, minimum distance to a stream or road, and existing versus all potential pads minimum distance between pads by Physiographic Section

Physiographic section	*N*		Minimum distance to a stream (m)			Minimum distance to a road (m)			*N*		Minimum distance between pads (m)		
	Existing	Permitted	Existing	Permitted	*P* value	Existing	Permitted	*P* value	Existing	All potential	Existing	All potential	*P* value
Allegheny front	10	14	349 ± 195	371 ± 141	1.000	364 ± 336	671 ± 550	0.452	10	24	5427 ± 5035	3220 ± 3437	0.229
Allegheny mountain	31	43	276 ± 128	282 ± 189	0.480	203 ± 158	245 ± 178	0.314	31	74	4620 ± 3645	2390 ± 2120	0.004
Anthracite valley	0	1	0	nd	nd	0	nd	nd	0	1	nd	nd	nd
Appalachian mountain	0	1	0	nd	nd	0	nd	nd	0	1	nd	nd	nd
Deep valleys	161	122	368 ± 159	378 ± 161	0.851	295 ± 314	383 ± 335	0.278	161	283	2043 ± 1801	1541 ± 1449	0.001
Glaciated high plateau	72	49	341 ± 195	400 ± 284	0.796	252 ± 213	340 ± 234	0.186	72	121	1452 ± 1033	1357 ± 750	0.402
Glaciated low plateau	580	300	357 ± 202	361 ± 208	0.477	240 ± 162	248 ± 178	0.831	580	880	1554 ± 1443	1265 ± 1145	<0.001
High plateau	25	21	300 ± 147	364 ± 248	0.767	260 ± 258	376 ± 368	0.511	25	46	3363 ± 6104	2075 ± 4548	0.609
Northwestern glaciated plateau	1	0	nd	0	nd	nd	0	nd	1	1	nd	nd	nd
Pittsburgh low plateau	273	230	315 ± 163	294 ± 163	0.500	249 ± 237	257 ± 200	0.408	273	503	1954 ± 2545	1718 ± 2023	0.060
Susquehanna lowland	36	28	302 ± 113	306 ± 122	1.000	189 ± 118	241 ± 130	0.371	36	64	2160 ± 1822	1407 ± 727	0.096
Waynesburg hills	276	184	248 ± 111	254 ± 115	0.703	240 ± 139	246 ± 148	0.954	276	460	1287 ± 1407	1103 ± 1057	0.060
Statewide	1465	993	325 ± 176	325 ± 185	0.835	247 ± 201	279 ± 229	0.114	1465	2458	1776 ± 2128	1466 ± 1844	<0.001

nd not determined

Table 3 Existing and permitted pad mean, minimum distance to a stream or road, and existing versus all potential pads minimum distance between pads by hydrologic basin

Hydrologic basin	*N*		Minimum distance to a stream (m)			Minimum distance to a road (m)			*N*		Minimum distance between pads (m)		
	Existing	Permitted	Existing	Permitted	*P* value	Existing	Permitted	*P* value	Existing	All Potential	Existing	All potential	*P* value
Allegheny	199	167	302 ± 152[a]	289 ± 162	0.345	222 ± 197	289 ± 300	0.172	199	366	2579 ± 3324	2167 ± 2623	0.194
Delaware	1	3	nd	245 ± 83	nd	nd	211 ± 122	nd	1	4	nd	10362 ± 4624	nd
Monongahela	259	208	256 ± 120	261 ± 142	0.967	227 ± 129	226 ± 128	0.820	259	467	1553 ± 1771	1168 ± 1235	0.004
Ohio	121	82	269 ± 133	301 ± 159	0.529	231 ± 155	274 ± 189	0.137	121	203	1598 ± 2486	1420 ± 1971	0.730
Susquehanna	885	533	358 ± 191	365 ± 201	0.546	261 ± 223	298 ± 237	0.005	885	1418	1365 ± 1621	1666 ± 1660	<0.001

nd No calculation possible due to sample size

[a] Mean ± standard deviation

Table 4 Existing and permitted pad mean, minimum distance to a stream or road, and existing versus all potential pads minimum distance between pads by Land Ownership Class

Land ownership	*N*		Minimum distance to a stream (m)			Minimum distance to a road			*N*		Minimum distance between pads (m)		
	Existing	Permitted	Existing	Permitted	*P* value	Existing	Permitted	*P* value	Existing	All potential	Existing	All potential	*P* value
Public	169	115	335 ± 198[a]	318 ± 212	0.184	217 ± 150	244 ± 200	0.904	169	284	1552 ± 1795	1439 ± 1611	0.057
Private	1296	878	324 ± 173	325 ± 182	0.541	251 ± 207	284 ± 232	0.007	2174	1296	1806 ± 2166	1470 ± 1872	<0.001

[a] Mean ± standard deviation

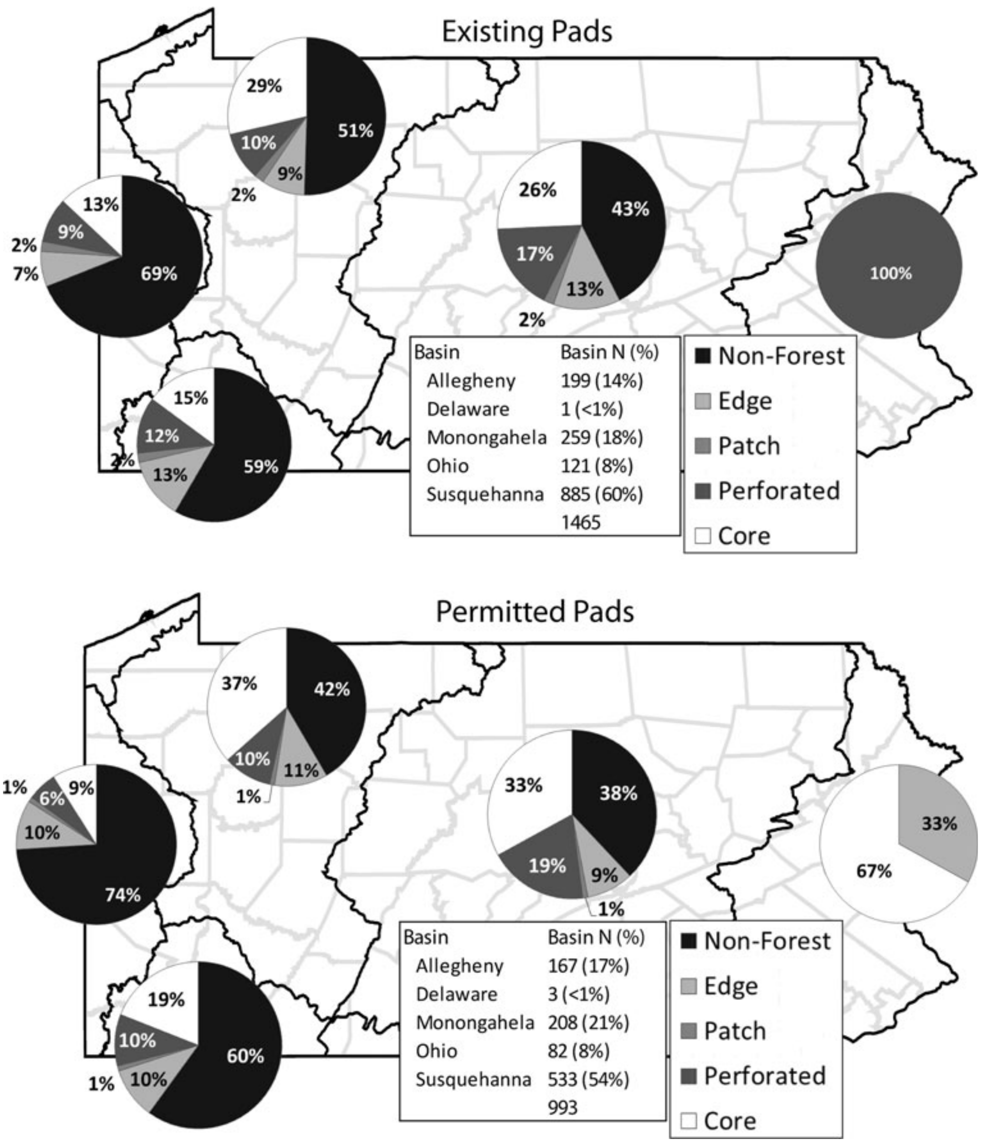

Fig. 4 PAMAP 2005 forest fragmentation classes for existing and permitted pads across and within major hydrologic basins

Accounting for existing pads, and potential development of all pads permitted as of June 3, 2011, 695 ha of core forest could be lost (Fig. 3). This value is likely an underestimate given that the loss of core forest will also result in the creation of new edge and perforated forest, which by definition would have previously been core forest.

Across major hydrologic basins (Fig. 4), existing pad development has been greatest in core forest in the Allegheny River basin (29 %), Susquehanna River basin (26 %), Monongahela River basin (15 %) and Ohio River basin (13 %). Permitted pad trends across basins suggest a greater proportion of pads could be developed in core forest in the Susquehanna River basin (33 %), the Allegheny River basin (37 %), and the Monongahela River basin (19 %), but the Ohio River basin could see a lower proportion of pads in core forest. Across the state's major hydrologic basins, the summed distance between all existing pads and their nearest road ranges from 29 to 231 km (22–159 km for permitted pads).

Across private versus public lands (Fig. 5), core and perforated forest represent the highest proportion of forest cover developed on existing pads or potentially developed in permitted pads. Whether existing or permitted pads are examined, private lands have more core forest developed, with perforated, edge, and patch following, respectively. Across existing pads, the cumulative distance to an existing road is 37 km on state land and 326 km on private land (28 km on state land and 249 km on private land for permitted pads).

Existing and permitted pads in core forest have the greatest distance to a stream or road, followed by perforated, edge, patch, and non-forest. Across existing pads, the cumulative distance to an existing road is 106 km in core forest, 55 km in perforated forest, 40 km in edge forest,

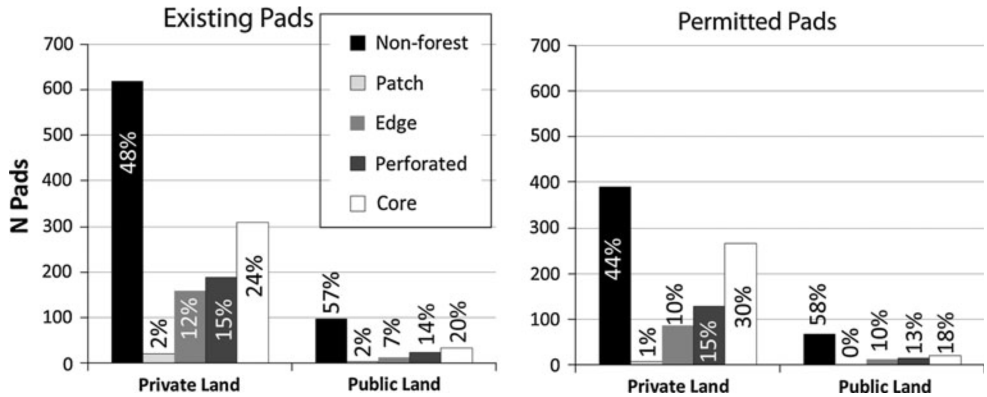

Fig. 5 PAMAP 2005 land ownership by fragmentation class across existing and permitted pads. Within existing or permitted pads, the proportion of pads on private or public land is presented relative to the respective total pads in that land ownership class

and 4 km in patch forest. Across permitted pads, the cumulative distance to an existing road is 102 km in core forest, 45 km in perforated forest, 24 km in edge forest, and 1 km in patch forest. There was no significant difference in the distance to a stream between existing and permitted pads (Table 5) for any fragmentation class; however, the distance to a road in perforated forest ($P = 0.047$) and core forest ($P = 0.086$) is significantly greater with permitted pads. The minimum distance between pads was significantly smaller for all potential pads versus existing pads in non-forest ($P < 0.001$) and core forest ($P = 0.009$) (Table 5).

Discussion

Land Cover Change Patterns

One objective of our research was to determine patterns of preexisting land cover where shale-gas pads are being developed. Our results indicate that shale-gas development in Pennsylvania is increasing rapidly with time; is largely concentrated in the northcentral, northeast, and southwest parts of the state; and is mostly on private land. The concentration of development on private land could pose a challenge to state and municipal government, private sector, and nongovernmental organizations managing land cover due to (i) a lack of centralized decision making across land management parties, and (ii) variable lease negotiation outcomes for each landowner affecting the land cover in which the pad is placed. Ownership of mineral rights (whether held by the landowner or gas developer) can play a very important role in land cover change because an owner with intact rights can somewhat guide infrastructure placement, but those without often cannot. Given that gas development is overwhelmingly occurring on private land, we believe the state would benefit from some form of regional planning to help manage shale-gas associated land cover change. For example, state and federal agencies, private citizens with leases, and gas companies could begin to work with communities to identify landscape restoration principles and practices (DellaSala and others 2003).

Our results suggest that drilling companies are beginning to construct pads with more wells per pad, although most pads still have 1–2 wells per pad. Development of more wells on fewer pads could provide the benefit of fewer pads throughout the state, with fewer new roads, gathering lines, and other associated infrastructure. This could result in undeveloped, or less developed, areas where ecosystem protection is maximized. However, the continuing development on multi-well pads would likely mean more local disturbance such as noise pollution, air quality degradation, or vibrations from traffic. Although it is unknown whether existing pads with 1–2 wells will be further developed, it would be preferable before construction of additional pads. Sharing of gas development resources could limit disturbance, but infrastructure from pads to main transmission lines is typically single-company owned, and knowledge of equipment/methods is often proprietary, so having two companies work together to share space may be difficult.

Contrary to our hypothesis, USDA NAIP land cover results (our most accurate land cover dataset) indicate more existing and permitted pads in agricultural land cover. However, the proportion of permitted pads in forest cover is greater than that of existing pads, suggesting that gas development in forest cover will increase. Using our USDA-NAIP land cover conversion data, and assuming construction of all permitted pads with a disturbance of 1.2–2.0 ha per pad (Johnson 2010; PADEP 2011a), 647–1078 ha of agricultural land and 538–896 ha of forest land could be developed if all pads permitted as of June 3, 2011, are developed.

Given that the Marcellus shale is widely distributed across the state, we were curious as to why the greatest amount of gas development is occurring on agricultural land. We believe two interrelated factors are responsible.

Table 5 Existing and permitted pad mean, minimum distance to a stream or road, and existing versus all potential pads minimum distance between pads by forest Fragmentation Class

Fragmentation class	N		Minimum distance to a stream (m)			Minimum distance to a road			N		Minimum distance between pads (m)		
	Existing	Permitted	Existing	Permitted	P value	Existing	Permitted	P value	Existing	All potential	Existing	All potential	P value
Non-forest	715	456	310 ± 172[a]	295 ± 196	0.487	219 ± 162	228 ± 167	0.829	715	1171	1769 ± 2144	1447 ± 1966	<0.001
Patch	24	8	320 ± 187	361 ± 196	1.000	178 ± 129	168 ± 99	1.000	24	32	2183 ± 2632	1491 ± 1281	0.280
Edge	171	98	322 ± 192	299 ± 170	0.222	232 ± 177	248 ± 181	0.765	171	269	1491 ± 1575	1376 ± 1487	0.282
Perforated	213	144	345 ± 188	339 ± 191	0.698	260 ± 216	313 ± 262	0.047	213	357	1796 ± 2228	1489 ± 2009	0.100
Core	342	287	346 ± 165	371 ± 196	0.162	311 ± 259	356 ± 283	0.086	342	629	1893 ± 2225	1526 ± 1668	0.009

[a] Mean ± standard deviation

First, gas development has progressed most quickly where the Marcellus formation is thickest (Harper 2008; USGS 2011), the gas is driest (MCOR 2011a) (and thus cheaper to process), and existing transmission lines are located (USEIA 2011a). The recent clustering of wells (MCOR 2011b), often indicated by smaller distances between all potential pads, reflects the tendency for wells to be drilled where production is best. Second, where gas development has occurred most rapidly (Fig. 1) spatially coincides with current land cover that consists largely of agricultural lands (PGDC 2011i).

The conversion of agricultural land to gas production, which would be expected to continue based on current trends, will be important to monitor. Although the converted area represents a small proportion of agricultural cover in Pennsylvania (3,116,079 ha (PADA 2011)), agricultural land under development for shale-gas occurs in a documented "food desert" region of the state (Ver Ploeg and others 2009; USDA-ERS 2011). Previous research has shown that the development of agricultural landscapes for urban sprawl puts pressure on remaining farmland (Heimlich and Brooks 1989; Arendt and others 1994; Dramstad and others 1996), and can result in the loss of more farmland due to indirect effects of farmland conversion (Brabec and Smith 2002). We hypothesize that similar effects could result from shale-gas development. However, the conversion of reclaimed gas infrastructure to greenhouse/hothouse or other suitable agricultural activities, powered onsite by natural gas, could present new food opportunities for surrounding communities. Recent observations by Penn State Extension educators indicate that some farms are no longer producing agricultural commodities and that agricultural supply networks (equipment dealers, insurance agents, etc.) have shifted to also supporting the drilling industry (Mark Madsen, personal communication).

Forest Fragmentation

Our results indicate that shale-gas development in Pennsylvania has caused, and will likely continue to cause, forest fragmentation, especially in core forest (Ritters and others 2002; Wickham and others 2010). As of June 2011, at least 695 ha of core forest have likely been developed due to shale-gas extraction (Fig. 3). However, this is likely an underestimate given that even more core forest would be lost via the creation of new edge around developed areas. The pace of current and future shale-gas development in forest cover suggests to us that protecting undeveloped core forest is critical, especially given the ecosystem services provided by these areas (Myers 1997). Our results support recent conclusions made by the DCNR, which reflect the risk of further development on state lands and the resulting loss of important forest habitat (PADCNR 2011b).

Road building to accommodate shale-gas pads is substantial. Assuming that the cumulative distance from a pad to an existing road represents the potential new road distance developed, then across Pennsylvania 367 km of new road have been built to existing pads, and 282 km of additional road could be built to permitted pads. Note that our road data may not capture all existing roads, but is the best available to date. Private land has more pads developed in forest cover than on state land, and private land has a greater cumulative road distance, indicating that road building in forest cover on private lands could lead to more forest fragmentation than on state lands. However, the number of pads between the two landowner classes differs significantly, which muddies the interpretation of how much road development is occurring. Using the ratio of cumulative miles developed to the number of pads can provide a normalized measure of road development intensity between public and private lands. A higher ratio would suggest greater road distance development for the number of pads built. Across existing and permitted pads, public land has a lower ratio than private land (0.21 and 0.25, respectively), but across public and private land the ratio increases with permitted pads (0.24 and 0.28, respectively). This suggests that road development on public land is less than on private land, and this is likely a reflection of current land management policy by the Pennsylvania DCNR (the land management agency with the most pads on public land). Current DCNR policy strives to place shale-gas pads close to existing roads (Dan Devlin, personal communication); exceptions for road distance may be made along roads with, or to, important scenic corridors. DCNR also tries to cluster pads to minimize overall forest disturbance (Devlin, personal communication).

Road development supporting shale-gas extraction could substantially change Pennsylvania's landscapes. Roads are known to contribute to the spread of invasive species (Mortensen and others 2009), negatively affect wildlife species and their habitat (Cushman 2006; Lindenmayer and Fischer 2006), and interrupt the movement of water across landscapes (Forman and Alexander 1998). Thus, we believe road development to support shale-gas extraction (whether resizing of existing roads or the creation of new roads) is a very important variable to monitor as development, and its effect on forest fragmentation, is tracked. Road development (Heilman and others 2002) has been previously identified as a useful metric for assessing regional forest fragmentation trends. Although we did not examine it, gas gathering line and water line development could also substantially fragment regional forests and should also be monitored due to similar effects on forest cover (Johnson 2010).

Risks to Waterways

Although across the state the minimum distance of a pad to a stream exceeded the state-required 30.48 m (100 ft) distance (mapped on a USGS quadrangle) (PADEP 2011d), our results suggest that stream water quality should still be a focus of protection as gas development progresses. We are most concerned about the Susquehanna River basin, where shale-gas development is most intense, forest cover is substantial, and cumulative road miles potentially developed (231 km) are one to two orders of magnitude greater than in other basins. The Susquehanna River basin also has pads with the greatest distance to a road, and the smallest distance between existing pads. Surprisingly, permitted pads in the Susquehanna River basin have the greatest distance between pads. The trend across existing pads suggests that more pads in the basin are being developed closer together, but in areas far from roads, which could promote more landscape disturbance. Note that forest fragmentation is already substantial in the Susquehanna River basin. The trend with the basin's permitted pads may suggest that gas development is spreading into more remote areas. Overall, the intense gas development in the Susquehanna River basin, and resulting landscape change, pose a risk to the Chesapeake Bay's aquatic resources and water quality. More efforts should be made to monitor gas development in the region, especially water resources.

Although our results suggest that pads across the state in non-forest cover are closer to streams than are pads in forest cover, such streams are likely already experiencing more severe water quality degradation than streams in forest cover (Drohan and DeWalle 2002). We believe that streams in forest cover, typically headwater streams in the study area, should become a focus of regional monitoring (especially in core forest where drilling is most active in forest cover). Although the distance from an existing pad to a stream is smaller on public versus private land (Table 4), surprisingly we found that permitted pads are closer to streams on public versus private land. The current, longer distance on public lands is likely a reflection of Pennsylvania DCNR land management policy, which aims to place pads farther from waterways (Dan Devlin, personal communication). The smaller distance with permitted pads on public land may reflect in unintentional result of pad clustering. Further research should investigate how pad management differs on public versus private land.

Conclusion

Given the fluctuation in estimates of extractable natural gas volumes (Urbina 2011; USGS 2011), natural gas prices

(USEIA 2011b; Walton 2011), and the ultimate economic impact of drilling (Kelsey and others 2011), it is difficult to estimate the potential spatial and disturbance footprint of shale-gas development in the region. Our results suggest that shale-gas development could substantially alter Pennsylvania's landscape. The loss of agricultural land with development presents some concern given that drilling is now competing with food production for space on the landscape. Across the greater Allegheny Plateau region, we would expect to see a lower percent of agricultural land lost in Kentucky and West Virginia (given that more land there is in forest cover (Heilman and others 2002); however, Ohio and New York could see agricultural land cover conversion on the scale of Pennsylvania's, given similar agricultural land cover patterns in their shale-gas regions (NYDEC 2011; OHDNR 2011). The development of new roads to support drilling could greatly alter landscapes. Assuming that all pads in our study (permitted as of June 3, 2011) are constructed, there could be 649 km of new road developed in Pennsylvania alone. Cumulatively, across the region, this could negatively affect forest ecosystem integrity via increased fragmentation. The fragmentation of forest land, especially northern core forest, places headwater streams, and their larger downstream waterways, at risk of pollution. Based on the intensity of development in the Susquehanna River basin, future expansion of shale-gas production in this basin could become a significant land and water management challenge for Chesapeake Bay services (food, ecosystem, and recreation).

The concentration of existing core forest in the northern part of the state, and the focus of drilling in this area (largely on private land), lead us to conclude that remaining areas of public land are key refuges for the protection of wildlife, ecosystems, and their associated ecosystem services, and that these areas should receive further protection. Current patterns of development on public versus private land suggest that an organized approach to siting drilling infrastructure could help minimize the development on forest lands and potential damage to waterways, and help manage development on agricultural land. Our results, while geographically specific to the state boundary of Pennsylvania, are certainly applicable to the greater Allegheny Plateau given its similarity across many states. Beyond the greater region of this study to Canada, the United Kingdom, and Europe, we expect that land managers will face similar consequences from shale-gas development. While there may be differences in the types of cover and basins being developed, or the degree of development, it is likely that development will proceed rapidly and follow a spatial pattern dependent on the resource's potential and not constraints of the landscape, its cover, or ecosystem value. As we have concluded in Pennsylvania, an organized effort across government and private entities may be a way to manage development, but like in the United States, achieving such a management strategy given mineral ownership differences, regional and national, or even international law will be a substantial challenge. In the European Union (EU), this could be especially challenging given the mechanisms of implementation of national versus EU law.

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