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Chapter 3: Changes to the Wyoming Basins Landscape from Oil and Natural Gas Development

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Abstract. Oil and natural gas have been produced in Wyoming since the late 1800s although the rate of extraction has increased substantially in the last two decades. Well pads, roads, and infrastructure built to support resource development alter native vegetation configuration; however, the rate and effect of land cover change resulting from oil and gas extraction has not been quantified across the region. We used a Geographic Information System (GIS) to model development through time and assess change to native vegetation at two spatial extents (field and subbasin) within the Wyoming portion of the Wyoming Basins Ecoregional Assessment (WBEA) area. Since 1900, a minimum of 1,703 km^2 of native vegetation in the WBEA area has been replaced by well pads or roads. Shrublands were, and continue to be, the dominant land cover class and the cover type most affected by oil and gas extraction. Average shrubland patch size has decreased by approximately 10% at the subbasin extent in the WBEA. Core area (≥60 m from edge) size declined by 13% as road development fragmented formerly continuous patches. To date, the majority of land cover change has occurred in formally identified oil and gas fields, which cover about 1% of the WBEA in Wyoming. Approximately 7.5% of shrubland within oil and gas fields has been converted to well pad or a road supporting a well, and shrubland patch size has declined by 45%. Resource reserves, especially natural gas, have been identified outside traditional fields, and development will likely expand as resource development becomes more cost-effective. Revegetation guidelines are in place for development areas addressed by Environmental Impact Assessments although no quantitative data are available to assess how well restoration efforts are restoring landscapes and connecting fragments.

Key words: fragmentation, GIS, land cover change, landscape, oil and gas development, shrublands, Wyoming.

Oil and natural gas extraction has occurred in Wyoming since at least 1884 (Keefer 1965). Before 1960, extraction activities were relatively dispersed because resource detection and delivery technologies were poor and access to resource rich areas was low. Since 1960, increasing demand and development of advanced technologies to extract reserves has driven an exponential increase in permit requests (Limerick et al. 2003) along with an increase in infrastructure needed to support extraction and delivery. Worldwide demand for energy has increased by more than 50% in the last half-century (National Petroleum Council 2007). Production of natural gas in the US has increased by 60% since 1990 (U.S. Department of Energy 2007), and current projections predict the trend to continue (National Petroleum Council 2007).

Natural gas produced in the western U.S. constitutes 20% of the United States' annual supply, and the region holds 41% of the nation's total natural gas reserve (Limerick et al. 2003). The area encompassed by the Wyoming Basins Ecoregional Assessment (WBEA, Fig. 3.1) is the center of the largest concentration of onshore oil and gas reserves in the contiguous 48 United States (U.S. Departments of the Interior, Agriculture, and Energy 2003).

The Greater Green River Basin, located primarily in southwestern Wyoming and northwestern Colorado, holds the largest volume of oil and natural gas reserves among the key geologic basins recently inventoried (U.S. Departments of the Interior, Agriculture, and Energy 2003).

A recent trend in the WBEA area is production of coal bed natural gas, also known as coal bed methane (CBM; Braun et al. 2002, Gilbert 2002, Morton et al. 2002, Noon 2002, Walker et al. 2007a). Potentially profitable CBM reserves have been identified in southwest Wyoming; the Greater Green River Basin alone is projected to contain eight times the CBM reserves of the already developed Powder River Basin (U.S. Departments of the Interior, Agriculture, and Energy 2003), and CBM development is well underway in the Pinedale Anticline area (Walston et al. 2009).

Well pad and road networks built to access oil and natural gas resources replace native vegetation on the landscape (Weller et al. 2002, Walston et al. 2009). However, the rate and extent of this replacement has not been quantified for the WBEA area. Here we applied spatio-temporal data and Geographic Information System (GIS) techniques to recreate changes in land cover distribution and configuration due to oil and gas development in western Wyoming.

Potential environmental effects from development of oil and gas wells and associated facilities are: (1) direct loss of habitat from road and well-pad development; (2) habitat fragmentation from road, pipeline, power line, and other facility construction associated with development; (3) temporary or permanent displacement of wildlife or range abandonment due to disturbance from vehicle traffic and noise associated with compressor stations and other well-related structures; (4) potential for increased soil erosion and consequent reduction in surface water quality; (5) invasion of exotic plant species facilitated by soil disturbance around structures and connecting corridors; (6) depletion of aquifers from pumping and discharge of millions of metric tons of water during extraction of methane in CBM fields; (7) changes in local hydrologic regimes as water is discharged into ephemeral streams; and (8) the potential for diseases such as West Nile virus to infect both humans and wildlife, a result from the creation of hundreds of water storage ponds for discharge from CBM wells (Table 1.3). Our objective was to estimate the direct loss and fragmentation of native land cover due to energy well and road development.

Habitat loss, degradation, and fragmentation associated with road development are increasing throughout the western U.S. (Forman et al. 2003, Gelbard and Belnap 2003, Thomson et al. 2005). Concern for the alteration, loss, and fragmentation of native shrubland has been voiced in the scientific literature (Rotenberry 1998, Braun et al. 2002, Bryner 2003, Knick et al. 2003), but few studies have quantified landscape-scale changes as a result of oil and gas development (Weller et al. 2002, Walston et al. 2009). Roads, highways, trails, and off-highway vehicles affect wildlife habitats and biological systems in many ways (Forman and Alexander 1998, Trombulak and Frissell 2000, Gucinski et al. 2001, Forman et al. 2003, Gaines et al. 2003). Effects of roads and trails range from disturbance of wildlife due to vehicle traffic (Lyon and Anderson 2003) to the function of roads as conduits for invasive plants (Bergquist et al. 2007; see Table 1.3 for a summary of road effects in the sagebrush [*Artemisia* spp.] ecosystem). Although past research focused largely on effects of roads and traffic on native ungulates (Berger 2004, Sawyer et al. 2006), other research has demonstrated negative effects of roads and vehicles on a variety of taxa, such as greater sage-grouse (*Centrocercus urophasianus*; Oyler-McCance 1999, Braun et al. 2002, Lyon and Anderson 2003), passerines (Ingelfinger and Anderson 2004, Gilbert and Chalfoun 2011), small mammals (Brock and Kelt 2004), and reptiles (Munger et al. 2003, Shine et al. 2004). Many other factors (i.e., surface mining, wildfire, urbanization, pipeline and power line construction, and livestock management) also influence sagebrush landscapes but were not included in this analysis because they are not well mapped (e.g., power lines) or have minimal effect in our focal area (e.g., urban development).

We provide a historical perspective on WBEA area land cover change as a result of oil and natural gas development. We modeled changes to the Wyoming Basins landscape resulting from development using temporally-precise data on well construction paired with the most accurate available data on road location to retrospectively delineate road and well construction trends over the last 110 years. We then overlaid these reconstructions on 30-m resolution land cover data to evaluate changes to shrublands and other common native vegetation types. We evaluated changes at two spatial extents: the field extent, which estimated changes within defined oil and gas fields designated by the Wyoming Geological Survey (De Bruin 2002), and the subbasin extent, which assessed change in the broader landscape resulting from oil and gas development within the WBEA area (Fig 3.1).

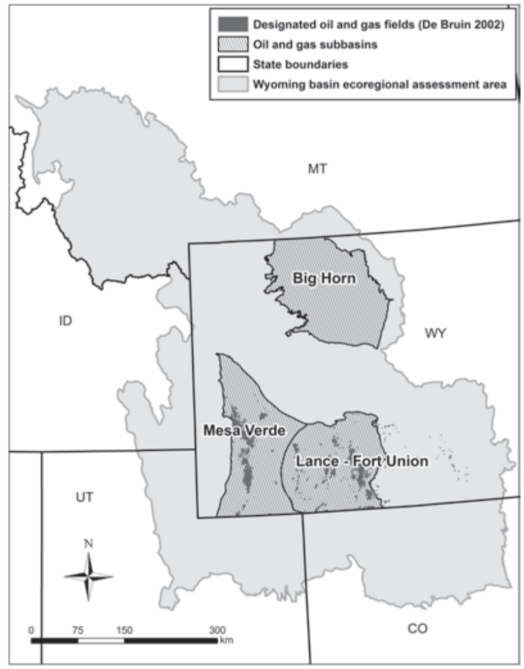

FIG. 3.1. Oil and natural gas fields and subbasins within the Wyoming portion of the Wyoming Basins Ecoregional Assessment (WBEA) area.

We restricted this analysis to the State of Wyoming (Fig. 3.1) because of the availability of consistent data on well construction and road location. Well location data was provided by the Wyoming Oil and Gas Conservation Commission (2009) and included the year that well construction was initiated for over 99% of records (n = 100,727). Road data, acquired from the U.S. Bureau of Land Management (BLM), was hand digitized from 2009 National Agriculture Imagery Program (NAIP) imagery at ~1:3000 screen resolution (U.S. Bureau of Land Management 2010) and contained over 500,000 road segments. Although BLM road data described 66% more roads than comparable data available from the U.S. Census TIGER data (M. O'Donnell, pers. comm.), evaluations made during our assessment indicated that BLM road data also underestimated amount of roads as much as 30%.

METHODS

Source Data

Source data (Table 3.1) used for this assessment were the most complete, consistent data sets available. We used the 30-m resolution LANDFIRE existing vegetation type (EVT) data layer (LANDFIRE 2007) to evaluate potential impacts on native vegetation. To increase thematic accuracy of mapped land cover types, we reclassified 102 land cover types that occurred in our study area to 10 land cover classes (Appendix 1.1).

Table 3.1. Source data used to create time series (1900–2009) land cover data in the Wyoming portion of the Wyoming Basins Ecoregional Assessment. LANDFIRE refers to the LANDFIRE existing vegetation type dataset (LANDFIRE 2007).

Date	Source data	Representing
1900	LANDFIRE, PRIMARY ROADS	Wyoming landscape without oil and gas development
1959	LANDFIRE, Primary Roads, Wells 1900–1959, roads – 1959	Oil and gas development in Wyoming through 1959
1969	LANDFIRE, Primary Roads, Wells 1900–1969, roads – 1969	Oil and gas development in Wyoming through 1969
1979	LANDFIRE, Primary Roads, Wells 1900–1979, roads – 1979	Oil and gas development in Wyoming through 1979
1989	LANDFIRE, Primary Roads, Wells 1900–1989, roads – 1989	Oil and gas development in Wyoming through 1989
1999	LANDFIRE, Primary Roads, Wells 1900–1999, roads – 1999	Oil and gas development in Wyoming through 1999
2009	LANDFIRE, Primary Roads, Wells 1900–2009, roads – 2009	Oil and gas development in Wyoming through 2009

GIS Analyses

Well and road construction

The LANDFIRE map included a developed cover class that identified roads and wells along with human population centers although visual inspection indicated these were under represented. Moreover, the data was static (at the time of the source imagery) and therefore did not have the temporal information contained in our vector-based source data. We elected to convert narrow linear (road) and small polygonal (well pad) developed patches back to a pre-construction cover class using the ArcGrid SHRINK command with a three-pixel (90 m) width. SHRINK uses a nearest neighbor process to reclassify cells within the "shrink" area to the most common class present in the surrounding pixels. Using SHRINK at 90 m effectively converted small developed patches to the surrounding values while maintaining larger patches (e.g., populated areas, surface mines), albeit at a slightly smaller size.

We modified the BLM road layer data for use in the ArcGIS Network Analyst (ESRI 2002) environment. Network Analyst facilitated dynamic modeling of realistic network conditions but required that points on the network (i.e., wells) were spatially overlaid on the linear network (i.e., roads). The source data for roads did not always include short access roads (i.e., resource roads, in BLM terminology) leading to well pads. Therefore, we generated a line from each well coordinate to the closest point on the source road layer using a custom Python script (Appendix 3.1). We then merged the newly created resource road layer to the initial BLM road layer and used this as our derived road network for analysis. This technique partially corrected for the approximate 30% underestimate of actual roads from the BLM layer.

Our next step was an iterative process to simulate well and road construction on the Wyoming landscape in approximate 10-yr time steps from 1900-2009 (the first iteration simulated development prior to 1959) using the Network Analyst Closest Facility (ESRI 2002) function. Closest Facility models the best way to get from one location (incident) on the network to another location (facility) based on user-defined criteria (impedance). We used the Closest Facility function to identify the shortest distance (impedance) from a well (incident) along the road network to an existing road intersection (facility).

We assumed that all county-maintained roads were present on the landscape prior to 1900, although not likely of the same construction type. We defined these as primary roads and extracted them from the source roads layer. Primary road intersections (nodes) were defined as facilities for the first Network Analyst iteration. Closest Facility was then used to generate a layer of roads associated with oil and gas wells drilled from 1900-1959. The Closest Facility function first produced a line feature that represented the shortest distance from each well to a node along the source road layer. This line feature was then merged to the primary roads layer to produce an estimate of roads on the 1959 landscape. Working in 10-yr intervals, we identified facilities (road intersections on the most recent road layer) and incidents (wells constructed in each decade) to create a road layer for 1969, 1979, 1989, 1999, and 2009 that represented our model of temporal road construction on the landscape.

The primary road layer, all six modeled road layers, and six temporally-identified well layers (representing existing wells from 1900-1959, 1900-1969, …, and 1900-2009) then were converted to raster layers using the extent of the disturbance footprint of each feature type (primary roads: 60 m, modeled roads: 30 m, well pads: 90 m) based on literature review, NAIP image evaluation, and the source data resolution (M. O'Donnell, unpublished data; E. T. Rinkes, pers.comm.). These were then merged with the LANDFIRE data to estimate land cover condition at the close of each decade starting in 1959.

Landscape metrics

To understand how oil and gas resource development has influenced the Wyoming landscape, we evaluated our derived spatial data using FRAGSTATS (McGarigal and Marks 1998), a spatial analysis pattern program for categorical maps. FRAGSTATS quantifies the areal extent and spatial configuration of patches within a landscape producing an array of landscape metrics. We generated patch size, edge density, core area size (defined as ≥60 m [2 pixels] from patch edges), and patch shape metrics to provide insight on how landscape and native land cover communities have changed due to oil and gas development. Computer limitations prevented generation of 30-m landscape metrics for the entire WBEA area so we ran FRAGSTATS at three broad-scale subsets (Bighorn Basin Province, Lance-Fort Union Composite, and the Mesa Verde Total Petroleum System) of the subbasin extent (Fig. 3.1). Subbasin boundaries were defined by U.S. Geological Survey National Oil and Gas Assessment (U.S. Geological Survey 2002).

Spatial scales of analyses

We conducted our analyses at two spatial extents to highlight differences among intensely developed areas and the larger landscape of western Wyoming. The subbasin extent approximates the larger landscape of the WBEA area within the state of Wyoming whereas the field extent quantifies landscape change within defined oil and gas fields (De Bruin 2002). De Bruin's (2002) oil and natural gas fields were derived by plotting all producing wells from a formation in an area and then assigning a 0.2-km buffer zone from each producing well to outline a field boundary.

We present raw landscape change trend data for field and subbasin extents. We did not statistically test the results because the developed land cover data were known to be incomplete. We estimated the proportion of missing road data by hand digitizing extant roads on six 162-km^2 ortho-images (1-m ground resolution; U.S. Geological Survey 2005) and comparing road densities to the source road data (U.S. Bureau of Land Management 2010).

RESULTS

Field Extent

Shrubland comprised 79.6% of the land cover prior to development (circa 1900) in designated oil and gas fields along with minor components of exotic land cover (7.0%), Grassland (4.1%), and other cover types (Table 3.2). Historically, shrubland patches tended to be much larger ($\bar{x}$= 36.9 ha, SE = 6.6) than average (all cover types; $\bar{x}$= 2.9 ha, SE = 0.4), and shrubland contributed to over 98% of habitat edges. Therefore, we focused our assessment on changes in designated oil and gas fields to shrubland land cover. Since 1900, approximately 10,237 wells have been drilled in designated oil and gas fields. We estimated that before development only 0.3% (12 km^2) of fields contained roads. By 2009, approximately 8.3% (286 km^2) of the native land cover had been converted to road or well pad, of which 97% (278 km^2) can be associated with oil and gas development. Within the 3,436 km^2 area of designated fields, 205.8 km^2 of shrubland had been converted to a well pad or road between 1900-2009 accounting for a loss of 7.5% of shrubland cover types. All other land cover classes showed declines (0.8-11.1%) except for the developed class, but the summation of these changes amounted to only 1.8% of fields (Table 3.2).

Shrubland patch sizes were reduced by 45.0% from 1900 to 2009, and core areas declined by 55.6% (Fig. 3.2). Habitat edge increased by 33% overall including a 26% increase in shrubland edge density (Fig. 3.2). Edge density and patch shape for classes other than shrubland and developed were little changed though these minor changes contributed to overall changes in landscape configuration. As expected, the most abrupt changes were observed in shrubland and developed landscape metrics, which resulted in an overall increase in landscape complexity. Developed patch shape and core areas exhibited notably different trends than other classes due to their linear shape and recent infilling of the heavily developed fields that led to well pad/road footprints merging on the landscape (Table 3.2, Figs. 3.2, 3.3).

Subbasin Extent

The WBEA landscape in the State of Wyoming, as represented by the three subbasins, is predominantly shrubland (61.0%) and forest (19.1%) with smaller amounts of grassland (6.5%) and riparian (4.1%) land cover types (these estimates vary slightly from others in this book [Ch. 1] because of different analysis extents and reclassification methods, see Appendix 1.1). Since 1900, 33,767 wells were drilled in the Wyoming portion of the WBEA (10,237 inside fields designated by De Bruin [2002], 23,530 outside those fields [Wyoming Oil and Gas Conservation Commission 2009]), and approximately 111,000 km of roads were constructed to service those wells. Well pad and road construction since 1900 converted approximately 0.97% (1,703 km^2) of native land cover to the developed class. To provide context, approximately 5.2% of the Wyoming portion of the WBEA in the three subbasins can presently be classed as developed based on the best available road data (U.S. Bureau of Land Management 2010). Therefore, about 20% of native land cover conversion to developed class was related to oil and gas development. Shrubland (78%) was the most commonly converted land cover followed by exotic (6%; although exotics may not have occurred at time of road construction) and grassland (6%). Only 3% of conversions occurred in riparian and <1% in forest cover types.

Discrete land cover patches historically were relatively small (2.7–3.2 ha) in the three subbasins that we analyzed (Big Horn, Mesa Verde, and Lance-Fort Union, Fig. 3.4), with shrubland patches consistently being the largest (24.5–45.1 ha). Shrubland patches had relatively large core areas (14.0–30.1 ha, SE = 8.8) compared to other patch types (1.3–1.8 ha; SE

Table 3.2. Landscape indices within designated oil and gas fields (De Bruin 2002) in Wyoming within the Wyoming Basins Ecoregional Assessment area, 1900–2009. Land cover classes derived and reduced from LANDFIRE existing vegetation type data (LANDFIRE 2007; Appendix 1.1) and metrics generated using FRAGSTATS (McGarigal and Marks 1995).

Class	Year	Total area (ha)	Percent of area	Patch size (ha) $\bar{x}$(SE)	Edge density (m/m^2)	Patch shape (SE)	Core area (ha) $\bar{x}$(SE)
Agriculture	1900	6,432	1.9	3.8 (0.8)	3.6	1.3 (0.02)	1.8 (1.2)
	1959	6,343	1.8	3.7 (0.7)	3.7	1.3 (0.02)	1.7 (1.0)
	1969	6,283	1.8	3.6 (0.7)	3.7	1.3 (0.02)	1.6 (0.9)
	1979	6,258	1.8	3.5 (0.6)	3.8	1.3 (0.02)	1.6 (0.9)
	1989	6,206	1.8	3.5 (0.6)	3.8	1.3 (0.02)	1.5 (0.8)
	1999	6,100	1.8	3.3 (0.5)	3.8	1.3 (0.01)	1.4 (0.7)
	2009	6,049	1.8	3.3 (0.5)	3.8	1.3 (0.01)	1.4 (0.7)
Forest	1900	3,749	1.1	1.1 (0.6)	3.2	1.1 (0.01)	0.4 (1.8)
	1959	3,733	1.1	1.1 (0.6)	3.2	1.1 (0.01)	0.4 (1.8)
	1969	3,726	1.1	1.1 (0.6)	3.1	1.1 (0.01)	0.4 (1.8)
	1979	3,724	1.1	1.1 (0.6)	3.1	1.1 (0.01)	0.4 (1.8)
	1989	3,665	1.1	1.1 (0.4)	3.2	1.1 (0.01)	0.4 (1.2)
	1999	3,617	1.1	1.1 (0.4)	3.2	1.1 (0.01)	0.4 (1.0)
	2009	3,608	1.0	1.1 (0.4)	3.2	1.1 (0.01)	0.4 (1.0)
Sparse/barren	1900	9,071	2.6	0.5 (0.01)	17.7	1.2 (0.003)	0.02 (0.02)
	1959	8,930	2.6	0.5 (0.01)	17.5	1.2 (0.003)	0.02 (0.02)
	1969	8,856	2.6	0.5 (0.01)	17.4	1.2 (0.003)	0.02 (0.02)
	1979	8,786	2.6	0.5 (0.01)	17.3	1.2 (0.003)	0.02 (0.02)
	1989	8,631	2.5	0.5 (0.01)	17.0	1.2 (0.003)	0.02 (0.02)
	1999	8,323	2.4	0.4 (0.01)	16.4	1.2 (0.003)	0.02 (0.02)
	2009	8,089	2.4	0.4 (0.01)	16.0	1.2 (0.003)	0.02 (0.02)
Shrubland	1900	273,555	79.6	36.9 (6.6)	76.5	1.4 (0.02)	22.4 (4.5)
	1959	270,517	78.7	32.7 (4.0)	71.5	1.5 (0.02)	19.2 (2.6)
	1969	268,834	78.2	31.1 (3.5)	78.7	1.5 (0.02)	18.0 (2.3)
	1979	267,220	77.8	29.6 (2.9)	80.8	1.5 (0.01)	16.8 (1.9)
	1989	264,594	77.0	27.2 (2.3)	83.9	1.5 (0.01)	15.1 (1.5)
	1999	259,143	75.4	23.6 (1.7)	90.1	1.5 (0.01)	12.4 (1.1)
	2009	252,969	73.6	20.3 (1.3)	96.4	1.6 (0.01)	10.0 (0.8)
Exotic	1900	24,905	7.2	0.8 (0.1)	36.3	1.2 (.003)	0.08 (0.1)
	1959	24,494	7.1	0.8 (0.1)	36.0	1.2 (0.003)	0.08 (0.1)
	1969	24,328	7.1	0.8 (0.1)	35.8	1.2 (0.003)	0.08 (0.1)
	1979	24,093	7.0	0.8 (0.1)	35.7	1.2 (0.003)	0.08 (0.1)
	1989	23,676	6.9	0.8 (0.1)	35.4	1.2 (0.003)	0.07 (0.1)

TABLE 3.2. Continued

Class	Year	Total area (ha)	Percent of area	Patch size (ha) x̄(SE)	Edge density (m/m^2)	Patch shape (SE)	Core area (ha) x̄(SE)
	1999	22,933	6.7	0.8 (0.1)	34.5	1.2 (0.003)	0.07 (0.1)
	2009	22,140	6.4	0.7 (0.1)	33.9	1.2 (0.003)	0.06 (0.1)
Riparian	1900	10,101	2.9	1.2 (0.1)	12.8	1.3 (0.007)	0.2 (0.1)
	1959	10,012	2.9	1.2 (0.1)	12.8	1.3 (0.007)	0.1 (0.1)
	1969	9,961	2.9	1.2 (0.1)	12.8	1.3 (0.007)	0.1 (0.1)
	1979	9,924	2.9	1.2 (0.1)	12.7	1.3 (0.007)	0.1 (0.1)
	1989	9,859	2.9	1.2 (0.1)	12.7	1.3 (0.006)	0.1 (0.1)
	1999	9,767	2.8	1.2 (0.1)	12.7	1.3 (0.006)	0.1 (0.1)
	2009	9,649	2.8	1.1 (0.1)	12.6	1.3 (0.006)	0.1 (0.1)
Grassland	1900	14,175	4.1	0.3 (0.06)	35.3	1.1 (0.002)	0.002 (0.005)
	1959	14,069	4.1	0.3 (0.06)	35.0	1.1 (0.002)	0.002 (0.005)
	1969	14,011	4.1	0.3 (0.06)	34.9	1.1 (0.002)	0.002 (0.005)
	1979	13,909	4.0	0.3 (0.06)	34.7	1.1 (0.002)	0.002 (0.005)
	1989	13,731	4.0	0.3 (0.06)	34.3	1.1 (0.002)	0.002 (0.005)
	1999	13,332	3.9	0.3 (0.05)	33.4	1.1 (0.002)	0.002 (0.004)
	2009	12,912	3.8	0.3 (0.05)	32.6	1.1 (0.002)	0.002 (0.004)
Woodland	1900	230	0.1	0.2 (0.03)	0.6	1.1 (0.009)	0.0005 (0.008)
	1959	227	0.1	0.2 (0.02)	0.6	1.1 (0.009)	0.0005 (0.008)
	1969	224	0.1	0.2 (0.02)	0.6	1.1 (0.009)	0.0005 (0.008)
	1979	224	0.1	0.2 (0.02)	0.6	1.1 (0.009)	0.0005 (0.008)
	1989	222	0.1	0.2 (0.02)	0.6	1.1 (0.009)	0.0005 (0.008)
	1999	219	0.1	0.2 (0.02)	0.6	1.1 (0.009)	0.0005 (0.008)
	2009	218	0.1	0.2 (0.02)	0.6	1.1 (0.009)	0.0005 (0.008)
Wetland/water	1900	252	0.1	0.3 (0.04)	0.6	1.1 (0.01)	0.008 (0.16)
	1959	252	0.1	0.3 (0.04)	0.6	1.1 (0.01)	0.008 (0.16)
	1969	252	0.1	0.3 (0.04)	0.6	1.1 (0.01)	0.008 (0.16)
	1979	252	0.1	0.3 (0.04)	0.6	1.1 (0.01)	0.008 (0.16)
	1989	251	0.1	0.3 (0.04)	0.6	1.1 (0.01)	0.008 (0.16)
	1999	251	0.1	0.3 (0.04)	0.6	1.1 (0.01)	0.008 (0.16)
	2009	250	0.1	0.3 (0.04)	0.6	1.1 (0.01)	0.008 (0.16)
Developed	1900	1,197	0.3	17.9 (4.4)	1.1	3.0 (0.25)	0.0 (0.0)
	1959	5,092	1.5	13.6 (2.7)	9.0	3.9 (0.19)	0.04 (0.01)
	1969	7,194	2.1	15.2 (3.2)	12.5	4.2 (0.19)	0.02 (0.02)
	1979	9,278	2.7	16.4 (3.0)	16.1	4.4 (0.18)	0.01 (0.03)
	1989	12,833	3.7	17.3 (2.9)	22.0	4.3 (0.17)	0.01 (0.06)

TABLE 3.2. Continued

Class	Year	Total area (ha)	Percent of area	Patch size (ha) $\bar{x}$(SE)	Edge density (m/m^2)	Patch shape (SE)	Core area (ha) $\bar{x}$(SE)
	1999	19,983	5.8	17.8 (2.8)	33.0	4.2 (0.14)	0.01 (0.17)
	2009	27,783	8.1	19.9 (3.1)	43.9	3.8 (0.13)	0.06 (0.10)
All	1900	343,669	100.0	2.9 (0.4)	91.4	1.2 (0.002)	1.5 (0.9)
	1959	343,669	100.0	2.9 (0.3)	97.4	1.2 (0.002)	1.4 (0.6)
	1969	343,669	100.0	2.9 (0.3)	100.1	1.2 (0.002)	1.4 (0.5)
	1979	343,669	100.0	2.8 (0.2)	102.7	1.2 (0.002)	1.3 (0.4)
	1989	343,669	100.0	2.8 (0.2)	106.7	1.2 (0.002)	1.3 (0.4)
	1999	343,669	100.0	2.8 (0.2)	114.1	1.2 (0.002)	1.2 (0.3)
	2009	343,669	100.0	2.8 (0.1)	121.7	1.2 (0.002)	1.1 (0.2)

= 0.3). A large proportion (75.6–82.0%) of the total edge had shrubland as one component. At these broad extents, landscape changes due to oil and gas development are relatively subtle. Shrubland patch size declined by 9.6–10.4%, whereas mean patch size of all land cover types declined by <1%. The mean size of shrubland core areas (≥60 m from edge) were reduced by 13.0–13.6%. Edge densities increased slightly (7.5–8.2%), and patch shape tended to become more irregular but only slightly so (Fig. 3.4).

DISCUSSION

Effects of Development on Land Cover Change

We used a retrospective analysis to estimate historical landscape condition in designated oil and gas fields and three subbasins within Wyoming portion of the WBEA area to provide a spatiotemporal perspective on land cover changes due to oil and natural gas development. Our objective was to assess how landscapes have changed during oil and gas development but recognize that other natural and cultural factors also have influenced land cover condition and change over the last century. Our results suggest that oil and natural gas extraction is driving important landscape change including loss and fragmentation of shrubland land cover. We estimated that at least 1,703 km^2 of native land cover in Wyoming portion of WBEA area has been converted to well pad or road over the last 110 years. Landscape change due to oil and gas development has been most acute within designated oil and gas fields. Whereas these alterations amount to only about 1% of the three subbasins assessed, conversion represents a much greater portion (7.8%) of the landscape in the more heavily developed designated oil and gas fields.

Beyond direct loss of native vegetation, shrubland patch size in the heavily developed fields has declined by 45% since 1900, suggesting that historically intact landscapes are being divided into smaller parcels. Shrubland land cover types were the most intensely fragmented by oil and gas development; other land cover types were not as affected. Shrublands, especially sagebrush, are of particular conservation concern because areas currently under development contain some of the highest densities of greater sage-grouse (Connelly et al. 2004, Kiesecker et al. 2009, Doherty et al. 2011, Naugle et al. 2011) and other sagebrush-obligate species (Knick et al. 2003, Wisdom et al. 2005) in western North America. Fragmentation (defined

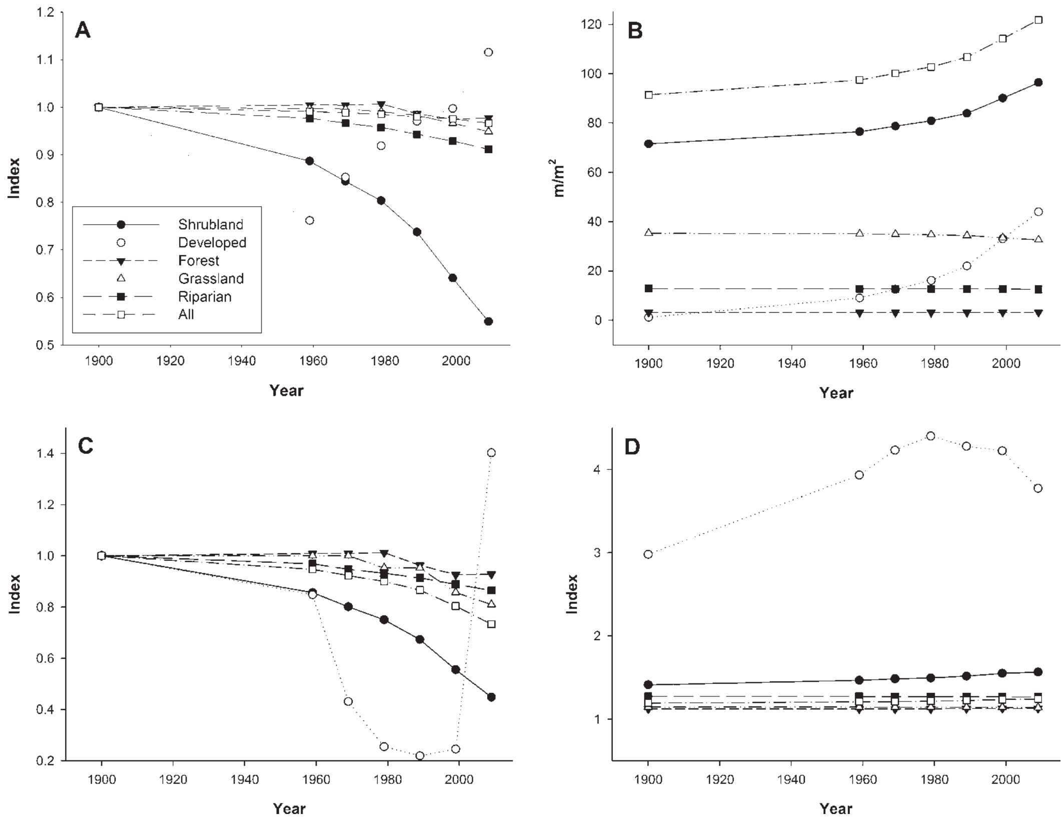

FIG. 3.2. (A) patch size (ha), (B) edge density (m/m^2), (C) core area size (ha), and (D) patch shape index of select land cover classes in oil and gas fields (De Bruin 2002) in the Wyoming portion of the Wyoming Basins Ecoregional Assessment area, 1900–2009. Years indicate all landscape change from energy development prior to and including year noted. Patch size and core area are graphed as departures from year 1900, set at 1.0.

as the loss of a natural habitat and division of remaining habitats into isolated patches [Wilcove et al. 1986]) of sagebrush may adversely influence native vegetation communities by altering microclimate factors such as light, soil, temperature, moisture, and wind conditions along patch edges potentially leading to altered plant composition and diversity (Saunders et al. 1991, Miller et al 2011). Shifts in composition and configuration of plant communities may be most detrimental to rare or sensitive species such as the 25 sensitive plant species present within the Jonah Field (U.S. Bureau of Land Management 2006). The BLM has established management criteria and mitigation plans for these species but acknowledged that "habitat loss (direct and indirect) would occur due to construction, and human presence would further reduce habitat quality in some of the remaining undisturbed or minimally disturbed areas. This would result in decreased populations of some…species," (U.S. Bureau of Land Management 2006:v. 4, p. 77).

Fragmentation can also alter the frequency and extent of fire, affect dispersal and regeneration of native plants, facilitate invasion by non-native plants (Bergquist et al. 2007), and strongly influence the spread of other disturbances (Daszak et al. 2000, Turner et al. 2001). Habitat loss and fragmentation due to human activities may be the most important factor contributing to the decline and

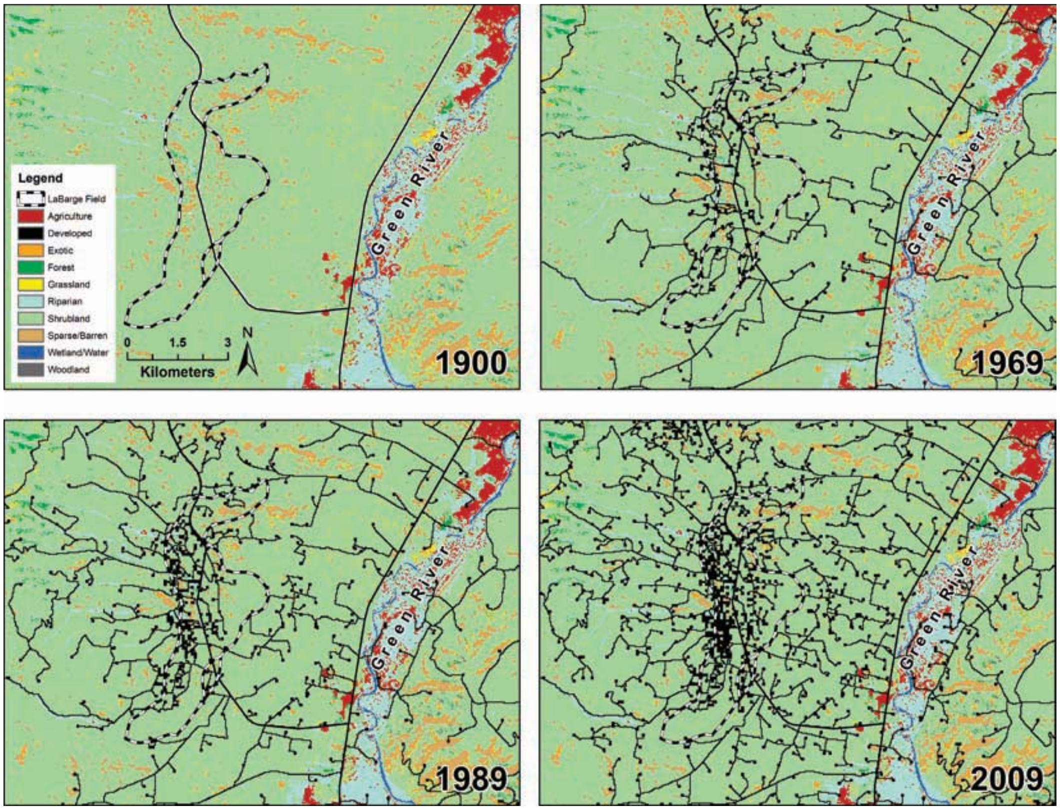

FIG. 3.3. Successive views of the LaBarge Oil Field area of southwest Wyoming, 1900–2009. Map center is approximately 110.24W, 42.30N. Years indicate all landscape change from energy development prior to and including year noted.

loss of native fauna in shrublands (Braun et al. 1976, Noss and Csuti 1994, Knick et al. 2003). Habitat fragmentation can have negative consequences for songbirds (Vander Haegen et al. 2000, Tewksbury et al. 2002, Inglefinger and Anderson 2004), greater sage-grouse (Holloran and Anderson 2005, Walker et al. 2007a, Doherty et al. 2008), pronghorn (*Antilocapra americana*; Berger 2004), and small mammals (Diffendorfer et al. 1995). However, landscape-scale effects, especially the consequences of fragmentation, have not historically been included in management assessments. Project-focused Environmental Assessments (e.g., U.S. Bureau of Land Management 2000, 2003) would benefit from this broader spatial perspective (Wisdom et al. 2005; Ch. 5–10).

Energy and associated road development also may impact wildlife directly through collisions with vehicles (Forman et al. 2003), mortality during construction, and human activity and noise disturbance that initiate behavioral modifications (e.g., Holloran and Anderson 2005, Sawyer et al. 2006). Collectively the amount of direct disturbance may encompass <8% of the landscape at the field extent. However, avoidance and stress by wildlife can extend the influence of each well pad, road, and facility into surrounding habitats (Walston et al. 2009) resulting in functional habitat loss (Aldridge and Boyce 2007). Zones of negative response can extend up to 3.7 km for ungulates (Sawyer et al. 2006). Sage-grouse hens captured on leks <3.2 km from energy development (well pad or road)

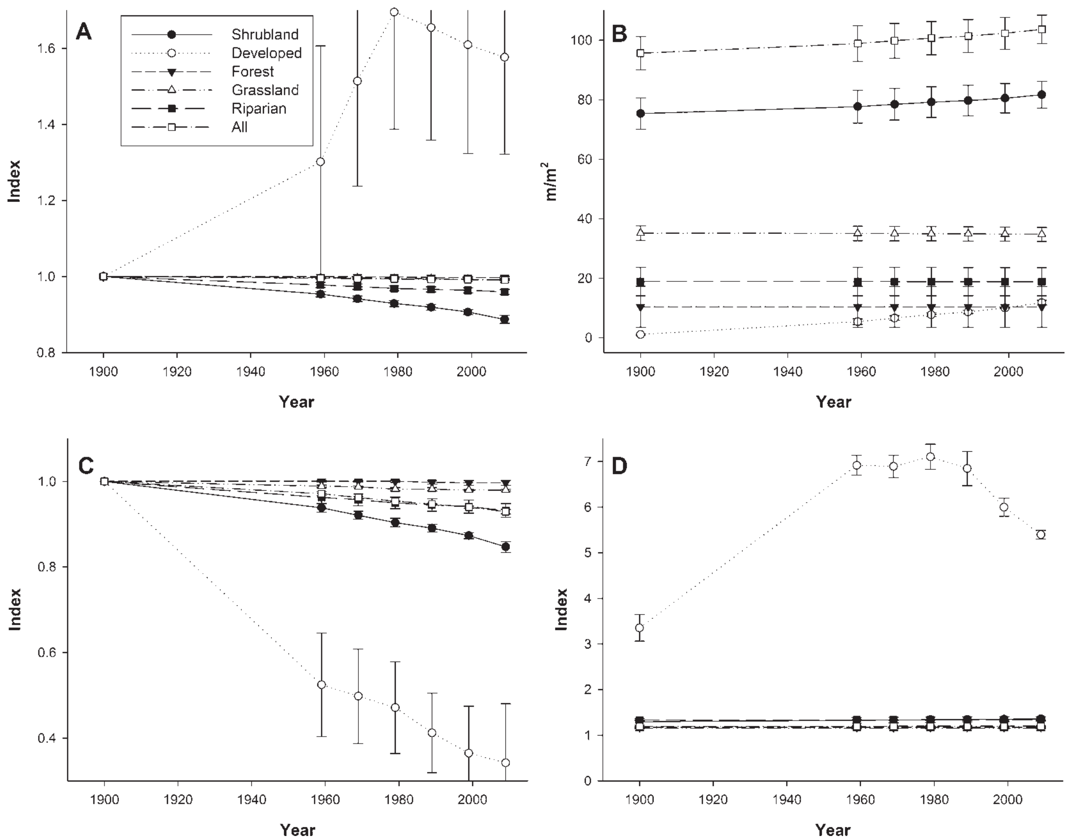

FIG. 3.4. Mean (error bars = SE) (A) patch size (ha), (B) edge density (m/m²), (C) core area size (ha), and (D) patch shape index in three subbasins (Bighorn Basin Province, Lance-Fort Union Composite, and the Mesa Verde Total Petroleum System) of the Wyoming Basins Ecoregional Assessment area, 1900–2009. Years indicate all landscape change from energy development prior to and including year noted. Patch size and core area are graphed as departures from year 1900, set at 1.0.

had lower nest-initiation rates and moved longer distance to nest sites than females on leks >3.2 km from any development (Lyon and Anderson 2003). Even low levels of oil and gas development and widely-spaced wells can negatively influence wintering distributions of greater sage-grouse (Walker et al. 2007a, Doherty et al. 2008) and lek persistence (Copeland et al. 2009). These examples suggest that avoidance or stress effects further compromise the value of remnant patches because wildlife may not use those patches effectively.

Additional questions about how oil and gas development influences ecosystem function, soil erosion, and water quality in western Wyoming remain unanswered. Data from the Powder River Basin and other areas undergoing energy development indicate that oil and gas extraction can introduce air pollutants and reduce water quality into formerly low-disturbance environments (Regele and Stark 2000, Bryner 2003, Peterson et al. 2009, Farag et al. 2010). Shifts in ecosystem functioning also may influence patterns and rates of land cover change in a negative feedback loop. Impacts to soils from removal of vegetation include exposure of the soil to wind and water erosion, mixing of soil horizons, loss of topsoil productivity, and soil compaction. Loss of vegetation and exposure of the soils could result in a loss of organic matter in the soil, increased runoff, erosion, and sedimentation (Furniss et al. 1991, McCaffery et al. 2007). These impacts might lead to a further reduction of native land cover thereby increasing landscape fragmentation and its effects on ecosystem function. For example, significant impacts to soils are anticipated under all project alternatives assessed for development in the Jonah oil fields in southwestern Wyoming (U.S. Bureau of Land Management 2006).

Introduction of groundwater to the surface, especially during CBM production may also influence ecosystem function. Discharge water is used for crop and livestock production, injected back into the ground, released into stream channels, or impounded on the surface in temporary reservoirs (Bryner 2003). Increased surface water associated with CBM production provides ideal habitat for mosquitos resulting in increased risk and mortality from West Nile virus in greater sage-grouse (Naugle et al. 2004; Zou et al. 2006, 2007; Walker et al. 2007b). Surface water impoundments are typically small (≤1 ha; T. Rinkes, pers. comm.) although there may be several ponds associated with a single CBM well. Impacts on the landscape from these ponds outlast the short lifespan of the surface water because residual salts or metals may compromise soil function after evaporation, and clay soils may become hardpan resulting in a permanent land cover shift in and around an impoundment. Not all wells have water impoundments but very few ponds created by natural gas extraction are mapped in Wyoming. Therefore, their contribution to the loss and fragmentation of terrestrial habitats is unknown and could not be measured with our analysis of land-cover change in relation to oil and gas development.

Caveats

Our retrospective analysis of WBEA land cover change resulting from oil and gas development is incomplete because data describing several change sources were not available. The source road layer we used is on the order of 60% more accurate than any previously available data set. However, our sampled assessment suggests it still underestimates roads related to development of oil and gas wells by as much as 31%. We estimated that 3,725 km (3.5% of initial source roads) of resource roads were not accurately represented in the initial source road layer based on the length of resource roads necessary to connect well locations to the nearest road. Additional evaluations within six 162-km^2 digital ortho-quarter quadrangles suggested the source road data underrepresented actual on-the-ground roads by 18–28%. Road construction occurs quickly during oil and gas development (Bryner 2003). Weller et al. (2002) estimated road density of 5.3 km/km^2 in the 430 km^2 Big Piney-LaBarge natural gas fields by carefully digitized roads from imagery. However, the road data we used (combined source roads and estimated resource roads) only had a road density of 3.1 km/km^2 in the same fields.

Power lines, pipelines, and other linear features that potentially fragment native land cover are not well-mapped and difficult to quantify. Many of these linear features are adjacent to roads and, therefore, some unknown portion is accounted for in the road layer, but cumulative effects of multiple disturbances should be further quantified.

Point infrastructure features such as gas compressors, pumping stations, storage tanks, retention ponds, and parking areas are also not well mapped. Consequently, their footprint is not represented in this analysis even though collectively they may represent more than 70% of the total surface disturbance of a fully operational CBM field (U.S. Bureau of Land Management 2003).

We did not quantify vegetation restoration efforts at dry wells or reclaimed well pads and roads. Restoration of disturbed areas at oil and gas development sites has been legally required since at least 1984 (U.S. Bureau of Land Management and U.S. Forest Service 1984). Typically, revegetation is applied to a reclaimed site within one growing season following well pad or road decommission. Monitoring follows within 1-2 years post effort and may continue for up to eight years. Criteria defining success and monitoring evaluations are typically qualitative (i.e., seedling production observed). Sites not meeting defined standards are often re-treated. Some portion of the native land cover that we classified as developed has been revegetated and would more correctly be assigned to a different class (i.e., exotic or shrubland). This may account for a portion of the missing resource roads in the original resource road layer developed from 2009 NAIP imagery. However, consistent monitoring data describing site reclamation in the Wyoming Basins are not available (D. Stroud, pers. comm.); therefore we cannot quantify that source of land-cover change.

Potential Uses of Data

Development of expansive oil and natural gas deposits that underlie crucial wildlife habitat constitutes one of the greatest contemporary challenges to the conservation of western wildlife (Wyoming Game and Fish Department 2005). Therefore, we assembled the spatial data presented here to provide a historic perspective of landscape changes and the opportunity to apply the data to retrospective analyses of wildlife population trends, modeling of future scenarios, and current and future land-use planning, mitigation, and natural resource management.

Future Development

Temporal trends in land cover change have accelerated in the last two decades, especially within designated oil and gas fields even though several fields had not yet been fully developed at the time of our 2009 analysis (Knick et al. 2011). Our assessment included only 1,195 wells in the Jonah Field, whereas 3,100 wells are expected to be drilled over the next decade (U.S. Bureau of Land Management 2006). The volume of natural gas in the Wyoming portion of the WBEA was estimated at 85 million cubic meters (Ayers 2002). Additionally, over 317 million cubic meters of oil remain to be recovered in the area *circa* 2002 (Energy Policy and Conservation Act 2002). Therefore, we expect more development and consequent landscape fragmentation throughout the WBEA.

Growth in U.S. energy demand is estimated at 0.5–1.3% annually (National Petroleum Council 2007), and demand for natural gas alone is expected to increase by 25% over the next 15 years (U.S. Department of Energy 2007). Therefore, it seems likely that the land-cover conversion rates we documented at the designated oil and gas field extent will become more commonplace across the larger WBEA. Presidential Executive Order 13212 (Bush 2001) expedited the review and approval of oil and gas development proposals in the western United States, indicating a continuing trend of energy development and subsequent conversion and fragmentation of native habitat in Wyoming. Similar developments are occurring in surrounding areas of Utah, Colorado, and Montana (Doherty et al. 2011), suggesting that the fragmentation we describe is also a potential consideration at a broader spatial extent.

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APPENDIX 3.1

Python script language to generate a new line dataset linking point locations to the closest node in line vector data set in ArcGIS 9.3. This process was used to create the resource road layer, linking oil and gas wells in Wyoming to the BLM road data (U.S. Bureau of Land Management 2010) for use in an analysis of landscape change due to oil and gas development in the Wyoming Basins Ecoregional Assessment area. This appendix is archived electronically and can be downloaded at the following URL: http://sagemap.wr.usgs.gov/wbea.aspx.