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REPORT

The effect of Appalachian mountaintop mining on interior forest

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Abstract Southern Appalachian forests are predominantly interior because they are spatially extensive with little disturbance imposed by other uses of the land. Appalachian mountaintop mining increased substantially during the 1990s, posing a threat to the interior character of the forest. We used spatial convolution to identify interior forest at multiple scales on circa 1992 and 2001 land-cover maps of the Southern Appalachians. Our analyses show that interior forest loss was 1.75–5.0 times greater than the direct forest loss attributable to mountaintop mining. Mountaintop mining in the southern Appalachians has reduced forest interior area more extensively than the reduction that would be expected based on changes in overall forest area alone. The loss of Southern Appalachian interior forest is of global significance because of the worldwide rarity of large expanses of temperate deciduous forest.

Keywords Appalachian mountains · Coal mining · Edge effects · Forest loss · Interior forest

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Introduction

The increase in Appalachian mountaintop mining (Table 1) was fostered by the confluence of technological innovation and the 1990 amendments to the Clean Air Act (Fox 1999; Szwilski et al. 2001; Burns (2005). Tighter restrictions on emissions included in the 1990 amendments to the Clean Air Act prompted the mining and electrical generation industries to favor sources of low-sulfur coal from the Appalachian region at about the same time that development of larger and more efficient machinery became available for excavation and removal. These mining activities are occurring predominantly in the Southern Appalachians, centered on southern West Virginia, eastern Kentucky and southwestern Virginia (US EPA 2005).

Table 1 Mountaintop mining methods

Steep-slope mining: coal mining and reclamation on natural slopes that exceed 20°, or on lesser slopes that require measures to protect the area from disturbance, as determined by the regulatory authority after consideration of soils, climate, the method of operation, geology, and other regional characteristics (30 CFR 716.2). Variances are provided so that reclamation does not have to return the land to its approximate original contour (AOC).
Source: Office of Surface Mining (4 August 2006; http://www.osmre.gov/rules/subchapterb.htm#V)
Mountaintop removal: coal mining and reclamation that remove entire coal seams running through the upper fraction of a mountain, ridge, or hill by removing all of the overburden and creating a level plateau or gently rolling contour. Variances are provided so that reclamation does not have return the land to its AOC (30 CFR 716.3).
Source: Office of Surface Mining (4 August 2006; http://www.osmre.gov/rules/subchapterb.htm#V)
Contour mining: A method typically used in mountainous areas of the eastern United States where coal seams are exposed in outcrops on hillsides and mountainsides. Mining that follows a coal seam along the side of a hill.
Sources: Office of Surface Mining (4 August 2006; http://www.osmre.gov/color5.htm)
Area Mining: A surface mining method that used in level to gently rolling topography or on relatively large tracts of land. Active area mine pits may be several miles long.
Source: Office of Surface Mining, Glossary: Acronyms and Terms (4 August 2006; http://arcc.osmre.gov/Glossary.asp)

The expansion of mountaintop mining in the Southern Appalachian region during the 1990s ultimately led to a lawsuit (Bragg versus Robertson, Civil Action No. 2:98-0636 US District Court, Southern District of West Virginia) in which the West Virginia Highlands Conservancy sued the West Virginia Department of Environmental Protection and the US Army Corps of Engineers alleging that deposition of mining spoil in nearby stream valleys violated the Clean Water Act (CWA) and Surface Mining Control and Reclamation Act (SMCRA) (US EPA 2005; TLPJ 1999). This court case and concerns expressed by other public and private entities resulted in an environmental impact assessment of mountaintop mining activities (US EPA 2005). Presumably because of the ongoing litigation, the environmental impact assessment focused primarily on watershed and water-quality impacts from depositing the overburden (rock overlying a coal seam) in nearby stream valleys, but also considered affects on: (1) groundwater and discharge; (2) interior forest birds; (3) noise and dust pollution and their potential impacts on human health, (4) success of re-vegetation of reclaimed mine sites, and several other factors (US EPA 2005). However, loss of interior forest per se was not considered as an environmental impact (US EPA 2005).

The ecological relevance of interior forest loss is equal to loss of water quality or interior forest birds. A host of ecological changes occur when forest changes from interior to edge (Laurance et al. 2002; Harper et al. 2005). Interior and edge forests are different in their composition, structure, and the ecological processes that govern them. Much of the forest cover throughout the Appalachians is interior because the forest is spatially extensive with little disturbance imposed by other uses of the land (Vogelmann et al. 2001; Riitters et al. 2002). Mountaintop mining poses a genuine threat to the interior character of Appalachian forests, and the threat is also globally significant because spatially extensive temperate deciduous forest is rare worldwide (Riitters et al. 2000).

The threat to Appalachian forests from mountaintop mining is compounded by the loss of the keystone (sensu O'Neill and Kahn 2000) ecological goods and services (Westman 1977; Costanza et al. 1997) they provide. There is less nutrient pollution to aquatic systems (Beaulac and Reckhow 1982; Frink 1991; Jones et al. 2001; Wickham et al. 2005), more moisture in the atmosphere (Hayden 1998; Pielke et al. 2002; Marshall et al. 2004), and a greater amount of habitat (SAMAB 1996; Robinson et al. 1995; Fahrig 2002) when the forest is spatially extensive and hence interior. The Appalachian region's recognized floral and faunal diversity (both aquatic and terrestrial) (Hinkle et al. 1993; SAMAB 1996; Pickering et al. 2003) is supported by the spatially extensive character of its forests.

The amount of interior forest loss is greater than the amount of forest loss resulting from a land-cover conversion because of spatial proximity (Skole and Tucker 1993; Weakland and Wood 2005). Interior forest that is adjacent to an area where forest is converted to another use loses its interior character because of the introduction of nonforest edges even though there was no ''direct'' conversion of the interior forest itself. In this report we will show that the loss of interior forest to mountaintop mining is greater than the amount of direct forest loss attributable to the practice. We will also show that the ratio of interior forest loss to forest loss increases as the impact of the disturbance (mountaintop mining) is considered over larger spatial scales.

Methods

We used temporal Landsat TM imagery (Fig. 1) and land cover from the circa 1992 and 2001 National Land Cover Databases (Vogelmann et al. 2001; Homer et al. 2004) to assess the impact of mountaintop mining on interior forest

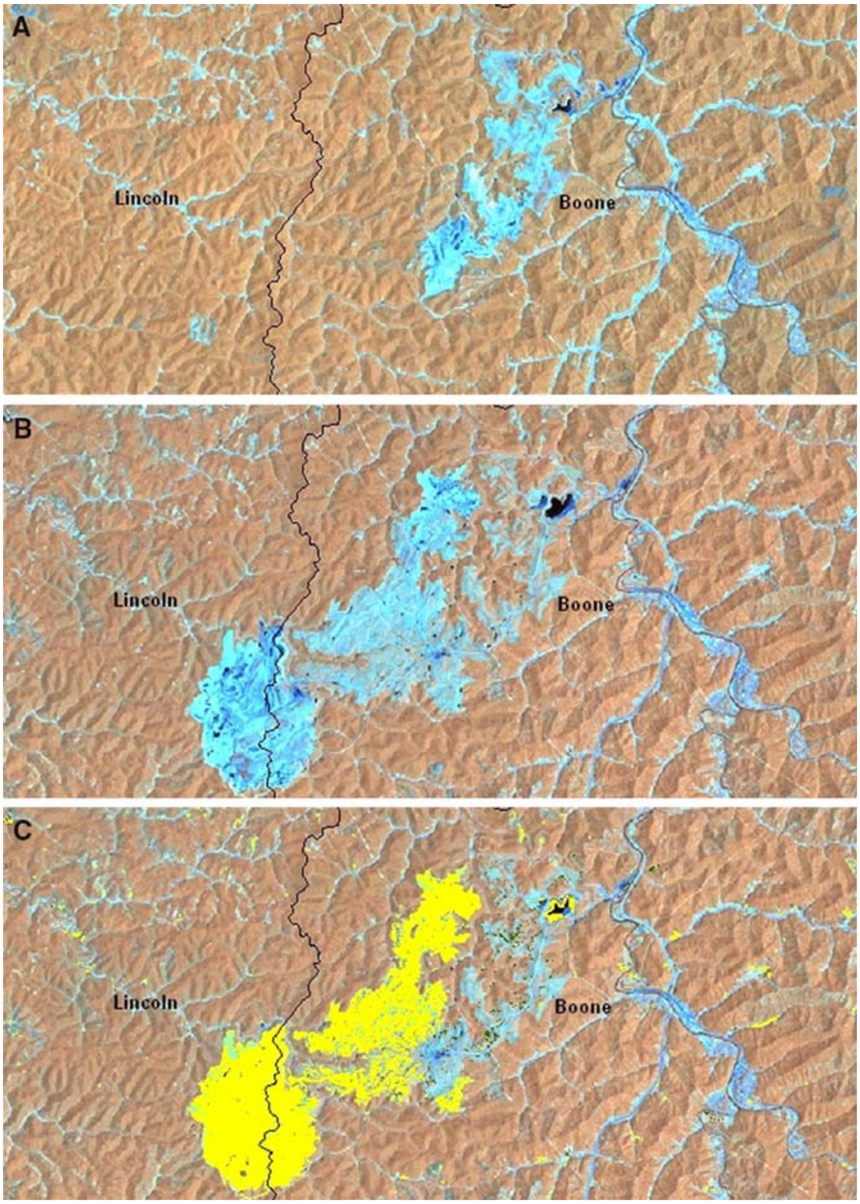


Fig. 1 False-color composite images of portions of Boone and Lincoln Counties in southern West Virginia for 1992 (A), 2001 (B), and 2001 with forest loss in yellow (C). Landsat TM bands 4, 5, and 7 are displayed in the red, green, and blue channels, respectively

loss. Methodological changes in land-cover classification between the circa 1992 National Land Cover Dataset (NLCD) (Vogelmann et al. 2001) and the 2001 NLCD (Homer et al. 2004) required additional calibration techniques to provide consistent land-cover classifications across the dates (Fry 2005). The calibration included six major steps: (1) both dates of the NLCD were reclassified from their approximate Anderson Level II to a coarser thematic Anderson Level I to establish areas of agreement; (2) areas of agreement were used as training data to generate individual decision-tree classifications (Homer et al. 2004) for each date; (3) new Anderson Level I classifications were compared to isolate types of change (including no change); (4) the new change and no change data were filtered with confidence thresholds from the decision tree to identify from and to labels; (5) the new, highest confidence areas (step 4) were used as training data for a second stage classification; (6) a final composite change map was created incorporating all prior intermediate steps. The land-cover change data resulting from the six-step calibration process were used to detect changes in interior forest.

Changes in interior forest at multiple spatial scales were estimated using image convolution: a fixed area window was moved over the land-cover maps one pixel at a time, and the number of forest pixels was recorded for the location of the center (focal) pixel. If a window was completely (100%) forested, the focal pixel was, by definition, interior for an area at least as large as the window. For each date, we tested square windows sizes of 2.25, 7.29, 65.61, 590.49, and 5,314.41 hectares (ha) (5.56, 18.01, 162.13, 1,459.13, and 13,141.47 acres, respectively). The corresponding side-lengths of the square windows were 5, 9, 27, 81, and 243 30-meter (m) pixels. One-half of the side-length approximates the linear distance between the focal pixel and the nearest nonforest boundary when the window is completely forested and nonforest occurs immediately adjacent to the window's edge. Sensitivity to the definition of interior forest was tested by relaxing the 100% threshold to 90%. Forest losses less than 0.45 ha (~1 acre) were ignored because binary classifications based on thresholds can be sensitive to small changes.

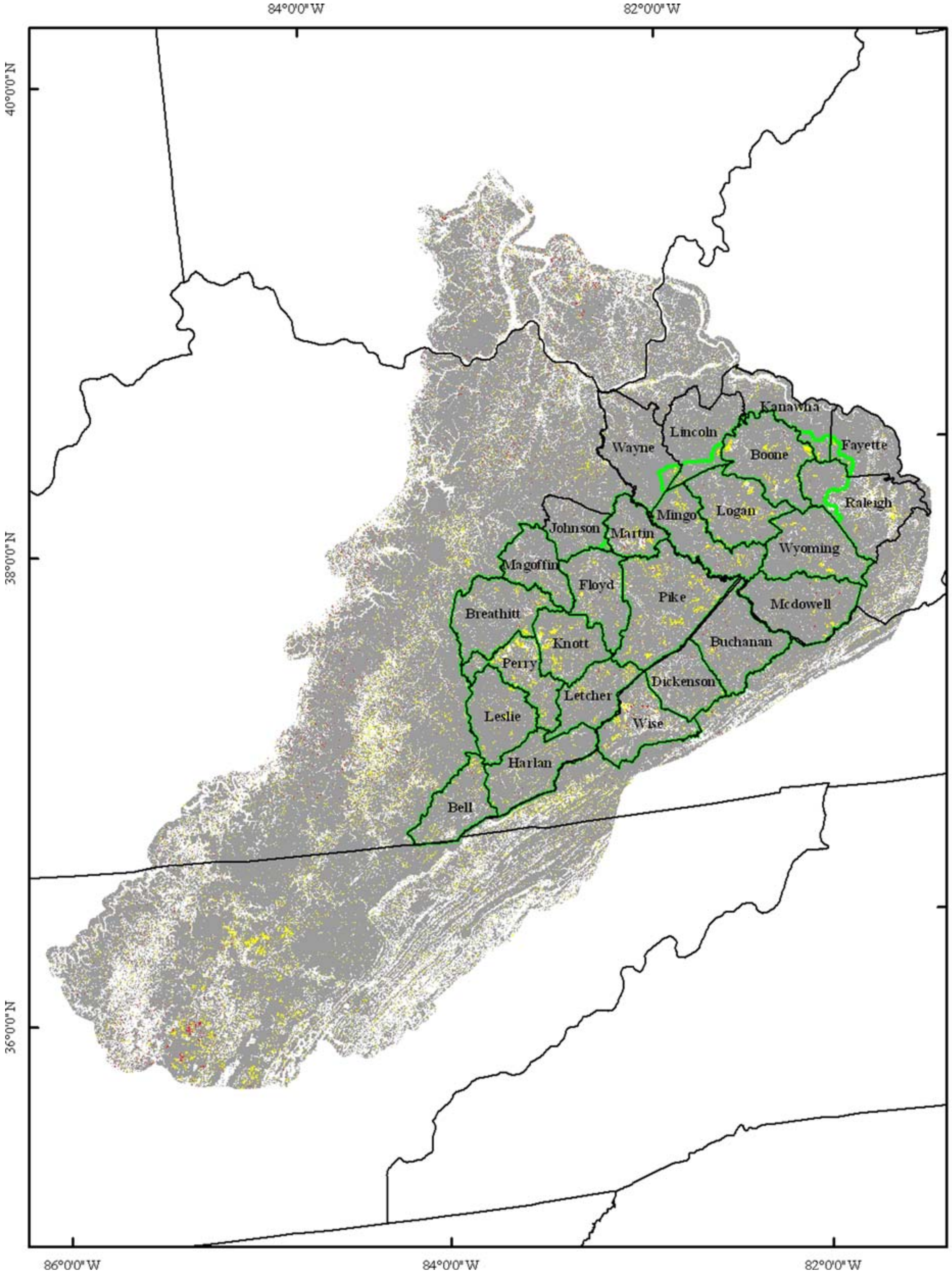
Fig. 2 The study area, outlined in green, covered a ▶ 19-county area in southern West Virginia, eastern Kentucky, and southwestern Virginia, plus smaller portions of Raleigh, Fayette, Kanawaha, Lincoln, and Wayne Counties in West Virginia, and Johnson County Kentucky. Forest on both dates is gray, forest loss is in yellow, and forest gain is red

Loss of forest due to factors other than mountaintop mining were excluded by examining color-composites of the Landsat TM imagery (Slonecker and Lacert 2001) to identify a smaller 19-county area (2,202,500 ha) where mining was the primary determinant of landscape change (Fig. 2). The county boundaries used to define the study area were adjusted when forest loss due to activities other than mountaintop mining were prevalent. For example, the green lines that do not track county boundaries in Fig. 2 were delineated to omit areas where mountaintop mining was not the primary driver of forest loss. To avoid bias near the study area boundary, image convolution was performed on the larger mapping region (Fig. 2) before extracting the smaller 2,202,500-ha study area.

Results

Approximately 95% of the 2,202,500-ha study area was forest in 1992, of which 4.2% was converted to another land cover by 2001. The estimated loss of interior forest ranged from 7.4% to 20.5% depending on the scale of analysis (Table 2A). Percentage interior forest loss was approximately 1.75–5.0 times greater that the percentage direct forest loss attributable to mountaintop mining. These results indicate that the loss of interior forest exceeded the actual amount of forest removed by mountaintop mining.

Relaxing the threshold used to define interior did not substantially change the ratio of interior forest loss to direct forest loss. Similar results were obtained when the threshold used to define interior forest was relaxed from 100% to 90% (Table 2B). Ratios of percentage interior forest loss to percentage direct forest loss were approximately 1.5–4.0 across the four smallest scales examined. There were no forested locales that met the 100% threshold for interior within the study area for the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84°0'0" W
82°0'0" W
Kanawha
Lincoln
Wayne
Boone
Fayette
Raleigh
Logan
Mingo
Johnson
Martin
Wyoming
Magoffin
Floyd
Pike
Mcdowell
Breathitt
Knott
Buchanan
Perry
Dickenson
Letcher
Leslie
Wise
Harlan
Bell

largest scale (Table 2A), but there were about 1.9×10^6 ha of interior forest at the 5,314.41-ha scale (1992) when the threshold was relaxed to 90% (Table 2B). Approximately 21% of the interior forest (90% threshold) at the 5,314.41 ha-scale was lost to mountaintop mining by 2001.

The effect of mountaintop mining on the cove and mixed mesophytic forests that characterize the region (SAMAB 1996) was similar to the effect on forest as a whole. Based on geographic overlay of our fragmentation results (e.g., Riitters et al. 2003) with the GAP (Scott and Jennings 1998) vegetation maps for southern West Virginia, ratios of interior forest loss to direct forest loss for cove and mixed mesophytic forest communities ranged from 1.7 to 9.0 and 1.6 to 13.5, respectively (Table 3).

Mountaintop mining has had a significant effect on large-scale interior forest (90% threshold). In 1992, there were approximately equal likelihoods of meeting the 90% threshold for interior forest at the 2.25-ha and 5,314.41-ha scales (Table 2B). By 2001, mountaintop mining produced a consistent decline in interior forest conditions with increasing scale so that there were no longer approximately equal likelihoods of meeting interior forest conditions at the smallest and largest spatial scales examined. One consequence of the loss of large-scale interior forest (i.e., 5,314.41 ha) is that it barely spans the 2,202,500- ha study area in 2001 (Fig. 3). In 1992, the 2,202,500-ha study area was the predominant area of large-scale interior forest within the larger mapping region (Fig. 3), whereas by 2001 it became difficult to traverse the 2,202,500-ha study area and stay within interior forest.

The United States Environmental Protection Agency estimated that the 4,856,247 ha (12,000,000 acres) Southern Appalachian region was 92% forest and that mountaintop mining will remove 6.8% of the forest between 1992 and 2012 (US EPA 2005). With that estimate as a guide, it is possible to extrapolate our results to estimate the loss of interior forest for the Southern Appalachian region impacted by mountaintop mining (US EPA 2005). Based on the results in Table 2A, about 84% of the forest in our study area was interior at the 2.25-ha scale in 1992, and 7.4% of it was lost by 2001. Using the appropriate percentages, there were 4,467,747 ha of forest in 1992 across the Southern Appalachian region, of which 3,752,908 ha would have been interior forest at the 2.25-ha scale. Using the same ratios between interior forest loss and forest loss as shown in Table 2A, a 6.8% loss of forest would translate to a 12% loss of interior forest at the 2.25-ha scale for the Southern Appalachian region, or 450,349 ha. Corresponding estimates of interior forest loss at the 7.29- 65.61-, and 590.49-ha scales are 502,010, 316,810, and 5,930 ha, respectively.

Discussion

The environmental impact assessment of mountaintop mining focused on water-quality impacts

Table 2 Change in interior forest from 1992 to 2001. Percentage loss is relative to the amount of interior forest in 1992. Ratio equals percentage loss divided by total forest loss (e.g., 7.4/4.2 = 1.76)

Window size (ha)	Interior forest, 1992 (ha)	Interior forest, 2001 (ha)	Difference (ha)	Percentage loss	Ratio
A. Total forest loss = 4.2%; threshold for interior forest = 100%					
2.25	1,751,185	1,622,303	128,883	7.4	1.76
7.29	1,430,336	1,284,095	146,241	10.2	2.43
65.61	463,821	371,477	92,344	19.9	4.74
590.49	8,814	7,008	1,806	20.5	4.88
5,314.41	0	0	0	0	0
B. Total forest loss = 4.2%; threshold for interior forest = 90%					
2.25	1,911,999	1,781,059	130,940	6.8	1.62
7.29	1,878,127	1,722,035	156,092	8.3	1.98
65.61	1,833,369	1,621,314	212,055	11.6	2.76
590.49	1,853,840	1,550,075	303,765	16.4	3.90
5,314.41	1,895,717	1,489,420	406,297	21.4	5.10

Table 3 Change in interior cove and mixed mesophytic hardwood forest types from 1992 to 2001. Percentage loss is relative to the amount of interior forest in 1992. Ratio equals percentage loss divided by total forest loss (e.g., 4.5/2.4 = 1.88)

Forest type	Scale	Interior forest 1992 (ha)	Interior Forest 2001 (ha)	Difference	Percentage loss	Ratio
A. Total forest loss = 2.4% (cove), 3.1% (mixed mesophytic); threshold for interior forest = 100%						
Cove	2.25	116,983	111,697	5,286	4.5	1.88
	7.29	101,686	94,485	7,201	7.1	2.96
	65.61	37,217	30,812	6,405	17.2	7.17
	590.49	279	219	60	21.5	8.96
	5,314.41	0	0			
Mixed mesophytic	2.25	404,022	381,217	22,805	5.6	1.81
	7.29	349,722	320,943	28,779	8.2	2.65
	65.61	134,703	109,432	25,271	18.8	6.06
	590.49	1,134	665	470	41.4	13.35
	5,314.41	0	0			
B. Total forest loss = 2.4% (cove), 3.1% (mixed mesophytic); threshold for interior forest = 90%						
Cove	2.25	122,432	117,522	4,910	4.0	1.67
	7.29	120,646	114,562	6,085	5.0	2.08
	65.61	116,010	106,691	9,319	8.0	3.33
	590.49	118,979	102,595	16,384	13.8	5.75
	5,314.41	123,806	99,772	24,034	19.4	8.08
Mixed mesophytic	2.25	428,159	406,467	21,692	5.1	1.65
	7.29	423,771	398,446	25,265	6.0	1.94
	65.61	416,314	383,081	33,233	8.0	2.58
	590.49	425,925	374,099	51,826	12.2	3.94
	5,314.41	439,505	369,391	70,114	16.0	5.16

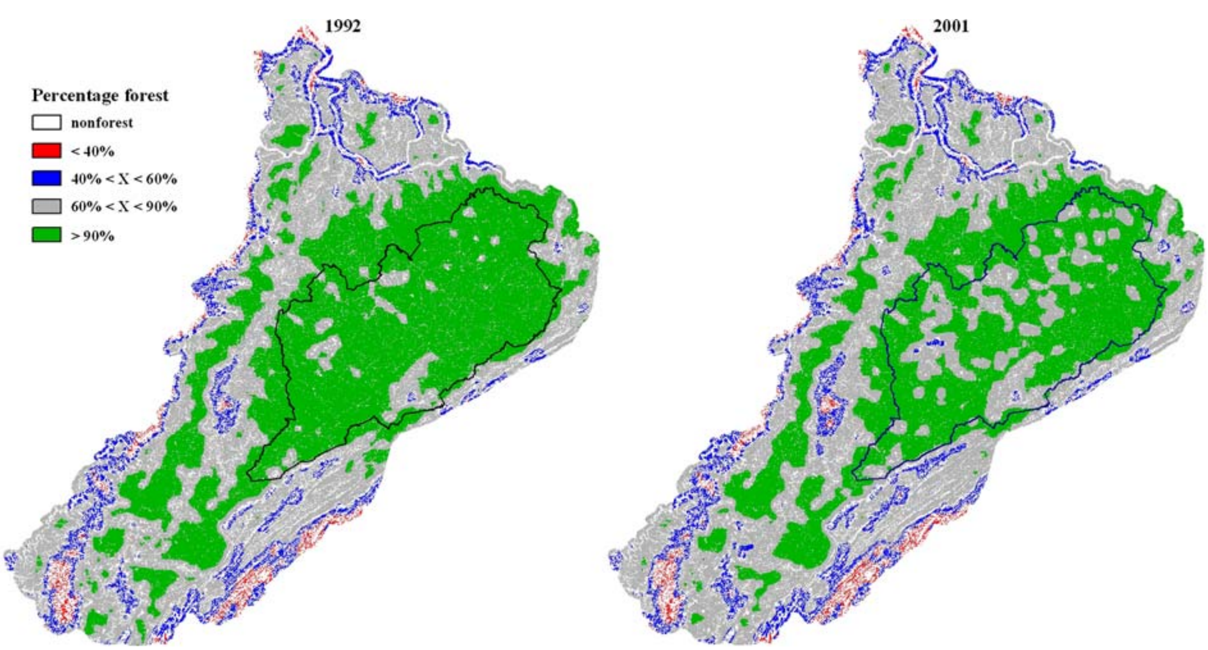

Fig. 3 Change in interior forest (90% threshold) at the 5,314.41-ha scale

related to sections 402 (point source discharges) and 404 (disposal of dredge and fill material) of the Clean Water Act, impacts on forest interior species, success of re-vegetation following reclamation, and other factors (USEPA 2005). The assessment did not consider possible impacts on the regional integrity of forest such as the loss interior forest. Our results indicate that interior forest loss is 1.75 to 5 times greater that the amount of forest loss attributable to mountaintop mining and that the ratio increases as the spatial scale of analysis increases. Similar ratios between interior forest loss and direct forest loss were found for cove and mixed mesophytic forest communities in the West Virginia portion of the study area.

Loss of interior forest in this study is not a loss of forest per se, but rather a change in the classification of forest from interior to edge. Fragmentation and introduction of edge change forest structure, composition, and ecological processes (Laurance et al. 2002; Harper et al. 2005). The condition and ecological functioning of forest changes from interior to edge. Forest edges have higher rates of atmospheric deposition (Weathers et al. 2001), higher proportions of exotic species (Harper et al. 2005), and fewer shade-tolerant taxa (Foster et al. 1998). Still, the effect of edges on forest is an emerging field (Harper et al. 2005), and one of the important issues is determination of ecological effects as a function of distance. Harper et al. (2005) reported edge effects that extended 100 m inward from the forest-nonforest boundary. Laurance et al. (2002) reported a maximum edge effect distance of 400 m, and Ramaharitra (2006) reported a maximum edge effect distance of 2,000 m. Our multi-scale analysis accounts for variability in the penetrating distance of the different edge effects reported in the literature. Edge effect distances of 100, 400, and 2,000 m are about equivalent to one-half of the side-lengths of 7 × 7, 27 × 27, and 133 × 133 30-m pixel windows, respectively. Our largest window size assumes edge effects from mountaintop mining penetrate approximately 3,650 m into adjacent forest. Future research may document edge effects penetrating 3.6 km into adjacent forest.

The spatially extensive character of forest in the Appalachians (Vogelmann et al. 2001; Riitters et al. 2002) provides the foundation for interior forest at large spatial scales. We estimate that mountaintop mining has changed between 1,806 and 128,883 ha of interior forest to edge (Table 2A), and the broader literature suggests that there are significant ecological differences between edge and interior forests. Our results also indicate that mountaintop mining is changing the spatial scale at which interior forest occurs in the region. At the 590.49-ha scale, interior forest occupied only 0.4% of the study area (8,814 ha) in 1992 and mountaintop mining eliminated about 20% of that very small proportion. It is not inconceivable that future activities will eliminate the remaining 590.49-ha scale interior forest, which would reduce the scale at which interior forest occurs in the region. The regional-scale loss of interior forest in Appalachia is of global significance because of the worldwide rarity of spatially extensive temperate deciduous forest (Riitters et al. 2000). Our results complement and extend the recently completed EIS (US EPA 2005) by quantifying an additional environmental impact and placing the impact in a global context.

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