RESEARCH ARTICLE

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Using Widely Available Geospatial Data Sets to Assess the Influence of Roads and Buffers on Habitat Core Areas and Connectivity

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Natural Areas Journal 28:261–274

ABSTRACT: Land development pressures that threaten habitat core areas and connectivity are intensifying across the nation and extending beyond urbanized areas in the form of rural residential development. This is particularly true in the temperate forests of the northeastern United States. We used a suite of nationally available data sets derived from satellite imagery to identify core habitat areas of the northeastern United States, including impervious cover (urbanized and developed areas) and forest cover (canopy density). These were augmented with road network extent and density. We analyzed the influence of different types of unimproved roads and amount of forest cover on identification of the extent and configuration of roadless areas, and then assessed these core habitat areas in terms of land ownership (public, private) and management (parks, refuges, multi-use). We also derived patch connectivity metrics using a graph theory approach, making use of cost surfaces that accounted for the above variables and associated landscape metrics. A case study linking suitable habitat for a keystone predator is explored. Because increased conversion and fragmentation of many roadless areas by exurban development will exacerbate the likelihood of local species extinctions, and complicate efforts to preserve intact functional ecosystems, our results suggest a starting point for the construction of a more comprehensive and ecologically functional reserve network for the region. The use of widely available data sets demonstrated the capability for similar analyses to be conducted nationally or for other regions.

Index terms: connectivity, conservation, graph theory, landscape ecology, roadless areas

INTRODUCTION

Habitat loss and fragmentation of the natural landscape resulting from urbanization are widely known to impact various aspects of biological diversity (Hansen et al. 2005). In the United States, 1.39 million km^2 of land were developed at urban and exurban densities as of the year 2000 (Brown et al. 2005). Low-density development, in particular, has increased rapidly and is now the dominant development pattern in the United States (Theobald 2001; Irwin and Bockstael 2002). Nearly 40% of all housing units are contained in areas typified by low density development in a matrix of natural land cover types (i.e., the wildland urban interface) (Radeloff et al. 2005).

The road building that accompanies development is a major contributor to habitat fragmentation (Watts et al. 2007). Roads also present barriers to wildlife movement, are a direct cause of mortality to wildlife, and act to increase introductions of non-native species (Mader 1984; Fahrig et al. 1995; Forman and Alexander 1998; Parendes and Jones 2000; Gibbs and Shriver 2002). Conversely, roadless areas have higher levels of native diversity and fewer invasive species (Glennon and Porter 2005). As development continues, we can expect roadless areas, those core habitat areas relatively unaffected by human disturbance, to decrease in size, number, and quality (Hansen et al. 2005). As a result, they will be ever more difficult to protect, particularly in historically more developed regions like the northeastern United States (Jantz et al. 2005).

Several assessments have noted the contributions that inventoried roadless areas (IRAs) could make to the conservation of biodiversity on U.S. Forest Service (USFS) lands (Noss et al. 1999; Strittholt and Dellasala 2001; Loucks et al. 2003). The addition of IRAs to designated wilderness areas would increase the representation of important biophysical characteristics in the nation's reserve network and enhance protection of threatened, endangered, or imperiled species on federal lands (DeVelice and Marti 2001; Loucks et al. 2003). Because of the ecological characteristics of roadless areas, much interest has been focused on prohibiting further road construction in IRAs. The USFS network of IRAs across the United States covers about 236,800 km^2 (U.S. Forest Service 2006). At present, road construction is allowed in about 60% of this area (U.S. Forest Service 2006). A lengthy review has resulted in the Forest Service recommending prohibition of additional commercial logging and road building in IRAs (Turner 2006), although the issue is politically charged.

Connectivity of landscape elements can play a critical role in species persistence and its loss can lead to localized extinctions long after the initial decrease in connectivity (Tilman et al. 1994; Carroll et al. 2004). Connectivity of core areas is also important in the context of species responses to climate change, with dispersal

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pathways between suitable habitat areas necessary to ensure species viability on longer time scales (Hannah et al. 2002). Due to the pace of landscape change in many areas, it is important to include characteristics of the intervening matrix when assessing connectivity (i.e., functional connectivity). This was not the case, however, in the USFS assessments noted earlier, where non-federal lands were not included (Turner 2006). In the context of climatic disruption, widespread pollution of air and waterways, and alteration of historic disturbance regimes, few areas in the east could be considered to exist in a "natural" state, determination of which would require a detailed assessment of current condition in relation to historical baselines. However, roadless areas are more likely than settled areas to maintain important elements of biodiversity and to be more resilient to continued human disturbance. Moreover, in order to assess the potential for remaining roadless areas to augment current conservation networks, it is necessary to determine their extent, management status, and landscape configuration across ownership boundaries.

Here we make use of remotely sensed and other spatial data sets in the eastern United States to: (1) identify forested roadless areas, here termed core areas, under different scenarios; (2) characterize core area management; and (3) analyze the contribution core areas make to landscape connectivity across the study area using a graph theoretic approach.

Borrowing from USFS roadless area criteria, core areas in our analysis had to be at least 2000 hectares, contain no improved roads, and be no closer than 500 m to the nearest improved road. In addition, we explored the influence of modifying these variables, and the amount of forest (tree) cover, on the derivation of core areas and associated connectivity. We discuss the connectivity analysis in the context of potential reintroduction of primary predators to the region. While our analysis was restricted to the eastern United States, the approach used nationally-consistent data sets and could, with minor modification, be extended to other regions.

DATA SETS

Roads and Developed Areas

We used a roads data set based on 1:100,000 United States Census Bureau TIGER line Files enhanced by Geographic Data Technology Inc. (GDT) and augmented with road classifications by ESRI (Environmental Systems Research Institute) (Table 1). Developed areas were identified using a map derived from Defense Mapping Satellite Program (DMSP) Operational Linescan System (OLS) imagery, which has the unique capability of detecting low levels of visible and near-infrared radiance at night. The DMSP-OLS data were converted to percent of impervious surface cover at 1 km resolution for the United States (Elvidge et al. 2004). We analyzed the accuracy of these maps in earlier work (Goetz and Jantz 2006).

Tree Cover

Tree cover information for the study area was obtained from a global, 500 m resolution, continuous fields tree cover map derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery (Hansen et al. 2003) (Table 1). The map consists of continuous values indicating the fraction of each 500 m pixel covered by trees (i.e., canopy density).

Protected Area Database

We used a national protected area database (DellaSala et al. 2001), consisting primarily of state level Gap Analysis Program (GAP) stewardship data compiled by the Conservation Biology Institute, which classifies land into one of four broad stewardship categories based on the level of protection particular ownership or management regimes afford biological resources (Scott et al. 1993) (Table 1). Category 1 and 2 lands are protected from conversion and are generally managed for maintenance of biological diversity. Examples of these include National Parks, State Parks, and USFS Wilderness Areas. Category 3 lands are protected from conversion but may be subject to use that degrades habitat quality, such as logging. Most USFS lands fall into this category. Category 4 lands are afforded no formal protections. Finally, we used a 1:1,000,000, U.S. National Atlas Water Feature data set of rivers, streams, and lakes to mask out water features (ESRI 2004).

METHODS

Scenario Development

To begin the process of identifying core areas, a line density function was applied to the roads data set. The function calculated the density of roads within a specified search radius from the center of

Table 1. Dates of acquisition, scale/resolution, and validation of datasets used.

Dataset	Date	Scale/Resolution	Accuracy
Roads	2000	1:100,000	Unassessed
Impervious Surface	1996 - 1997	1 km	Root Mean Squared Error of 11.30 (Elvidge et al. 2004)
Tree Cover	2001	500 m	Misclassification error of 11.5% (Hansen et al. 2002)
Protected Areas Database	1970 - 2006	1:100,000 or finer	Unassessed
Water Features	1995 - 2002	1:1,000,000	Unassessed

each 250 m x 250 m pixel of an overlying grid. This resulted in a 250 m resolution grid layer for the study area, the values of which reflect the linear distance of road, in meters per square kilometer, within the specified distance from the pixel center. A 250 m cell size (grain) was used to accurately capture the detail of core areas while minimizing computational requirements. The search radius, which was set to 500 m, functioned as a buffer depth so that any road within this distance would be identified and avoided in the selection process. Buffer depth refers to the minimum distance from core area edge to the nearest road. For a baseline case, unimproved roads, generally defined as one lane dirt roads not passable by a standard passenger car, were excluded from the roads database and were, therefore, not detected by the density function, effectively permitting their presence in core areas.

From the resulting grids, water bodies were removed to eliminate spurious core areas and cells with a density value of zero were extracted. After applying a function which identified discrete, contiguous groups of cells, groups of cells with a minimum size of approximately 2000 hectares were identified. The mean tree cover of each area was then calculated. Those areas with values less than 60%, a commonly used threshold used to distinguish between forest and woodland cover types, were removed from the initial analysis (Grossman et al. 1998). Finally, the mean impervious surface area of each core area was calculated using the impervious surface map. This was done to verify that the identified core areas were free of structures and other elements of the built environment.

For the baseline scenario described above, a 500 m buffer depth was used and unimproved roads were allowed in core areas. Four additional analyses were conducted to explore the effects of buffer depth, unimproved roads, and tree cover on our identification of core areas: (1) buffer depths were increased from 500 m to 800 m, (2) unimproved roads were not allowed in core areas, (3) buffer depths were increased and unimproved roads excluded, and (4) the 60% tree cover threshold requirement was removed.

After identifying core areas, ownership/management status was summarized for the study area in its entirety and on a state by state basis. Categories 1 and 2 were combined because of their similar emphasis on protecting biodiversity. While the data set did not include comprehensive data for private lands in the study region, we assumed that stewardship information for governmental entities was complete and any area not owned by federal, state, county, or local governments was private and unprotected and would, therefore, be classified as category 4 lands.

Landscape Configuration Metrics

The number, mean area, and mean perimeter area ratio of core areas were calculated for the baseline scenario. Core area metrics were calculated using Fragstats 2.0 (McGarigal et al. 2002) on a state by state basis as well as by management status.

Connectivity was calculated using a graph theoretic approach, which models the landscape as a set of nodes (patches) connected by edges (paths), the set of which are termed a graph. Matrix operations can be performed to investigate how individual nodes contribute to landscape connectivity or how well connected an entire landscape is. Path distance between nodes can be defined as Euclidean, or a functional definition can be used that incorporates relevant surrogates of landscape permeability such as road density and forest cover. Graph theory also permits incorporation of more detailed data sets as they become available, and can be used to assess the effects of scale (Urban and Keitt 2001; Urban 2005). The availability of detailed remotely sensed and other spatial data sets makes the approach particularly suitable for assessing connectivity over large areas. Core area connectivity was approached from the perspective of a theoretical, terrestrial species with no dispersal threshold and no defined time period for dispersal. Our assumption was that higher forest cover areas would provide less exposure to human contact, be more traversable for the theoretical species, and that human disturbance (roads, development, and agriculture) and water barriers would decrease traversability.

First, a cost surface was created to calculate the functional distance between core areas. The cost surface incorporated tree cover, impervious surface cover, road density, and water bodies. Percent tree cover was subtracted from 100 to create a new map where cells with lower values would be more costly and cells with higher values of tree cover would be less costly to traverse. So that all variables were weighted equally, road density was transformed to range from 0 to 100. The transformed road density map was then combined with the impervious surface and tree cover maps, creating a map with values between 1 and 300. Water bodies were assigned a value of 300. This resulted in a composite index of human disturbance and tree cover.

Interpatch connectivity was assessed with recently developed software called ArcRstats, which uses a graph theoretic approach to identify least cost paths between habitat patches from which network connectivity metrics are calculated <http://www.nicholas.duke.edu/geospatial/software>. ArcRstats requires two inputs, habitat patches (i.e., core areas) and a cumulative distance surface, derived from the cost surface, the values of which indicate the distance from a particular cell to the nearest habitat patch, taking the cost of traversing intervening cells into account. Patch level connectivity metrics derived from least cost paths between patches incorporate aspects of the surrounding landscape, allowing for evaluation of each patch's contribution to different aspects of overall landscape connectivity. The cumulative distance grid was converted to a triangulated irregular network (TIN), which is a three dimensional surface representation. "High elevation" areas of the TIN correspond to areas more costly for a theoretical species to traverse. Least cost paths between core areas were calculated from edges and nodes extracted from the TIN. Because of the considerable computational requirements of calculating least cost paths for the study area, the cost surface was degraded to 5000 m spatial resolution and a minimum vertical difference threshold of 3% of the maximum vertical difference in the TIN was specified (~50,000 functional distance units). Vertical differences less than this threshold were not resolved in the TIN.

From the least cost paths, three patch level centrality metrics were calculated: (1) the fraction of shortest paths that go through each patch (betweenness), (2) the fraction of possible nodes connected to each patch (degree), and (3) one divided by the average distance to all nodes from each patch (closeness). We summarized these metrics by management status and assessed their significance for landscape connectivity at different scales.

Case Study of a Keystone Predator

Because of the great interest generated for its reintroduction in the Northeast, we used the gray wolf, *Canis lupus*, as an example of a keystone species to assess current landscape connectivity between high quality habitat areas in upper New England–from the Adirondacks of New York to the Canadian border. Visual inspection of least cost paths generated separately for the region revealed critical areas where connectivity between core area clusters was maintained by a small number of patches. We buffered these least cost paths by 5 km on either side creating a 10 km wide corridor encompassing "stepping stone" core areas which connect larger core area clusters. We calculated area, percent tree cover, percent impervious surface cover, and road density for the corridor. Based on these metrics, we used results from the literature on wolf dispersal and habitat requirements to assess the suitability of this corridor for providing suitable habitat connectivity in the region.

RESULTS

Baseline Case

For the baseline case (500 m buffer, unimproved roads included) 1177 discrete core areas covering 73,370 km^2 were identified–approximately 8% of the study area (Figure 1) (Table 2). Core areas were present in every state with the exception of Rhode Island. On a state by state basis, Maine and New York contain the greatest absolute extent of core area. When core area is calculated as a percent of state area, Maine and New Hampshire rank highest.

Table 2. Roadless area (km^2) in each state considering the influence of differing buffer zone depths and unimproved roads.

		500 m buffer				800 m buffer			
		Unimproved Roads		No Unimproved Roads		Unimproved Roads		No Unimproved Roads	
State	State Area	Area	Percent	Area	Percent	Area	Percent	Area	Percent
Maine	84,135	23,153	28	21,171	25	16,353	19	14,645	17
New Hampshire	23,983	4,783	20	4,355	18	3,305	14	3,010	13
Vermont	24,950	3,475	14	2,900	12	2,044	8	1,565	6
New York	125,773	14,620	12	12,905	10	10,883	9	9,232	7
West Virginia	62,690	5,625	9	3,025	5	2,255	4	1,021	2
Tennessee	109,181	5,785	5	4,439	4	2,833	3	2,099	2
Virginia	103,515	4,609	4	3,323	3	1,887	2	1,216	1
North Carolina	127,605	4,933	4	4,429	3	2,875	2	2,523	2
Pennsylvania	117,298	4,271	4	3,605	3	1,498	1	1,242	1
Kentucky	104,525	1,725	2	1,310	1	352	0.3	178	0.2
Massachusetts	21,075	218	1	113	1	52	0.2	50	0.2
Delaware	5,309	26	0.5	26	0.5	0	0	0	0
Connecticut	12,895	61	0.5	28	0.2	0	0	0	0
Maryland	25,397	59	0.2	58	0.2	19	0.1	19	0.1
New Jersey	19,795	25	0.1	25	0.1	0	0	0	0
Rhode Island	2,838	0	0	0	0	0	0	0	0
Total	970,965	73,370		61,711		44,354		36,802	

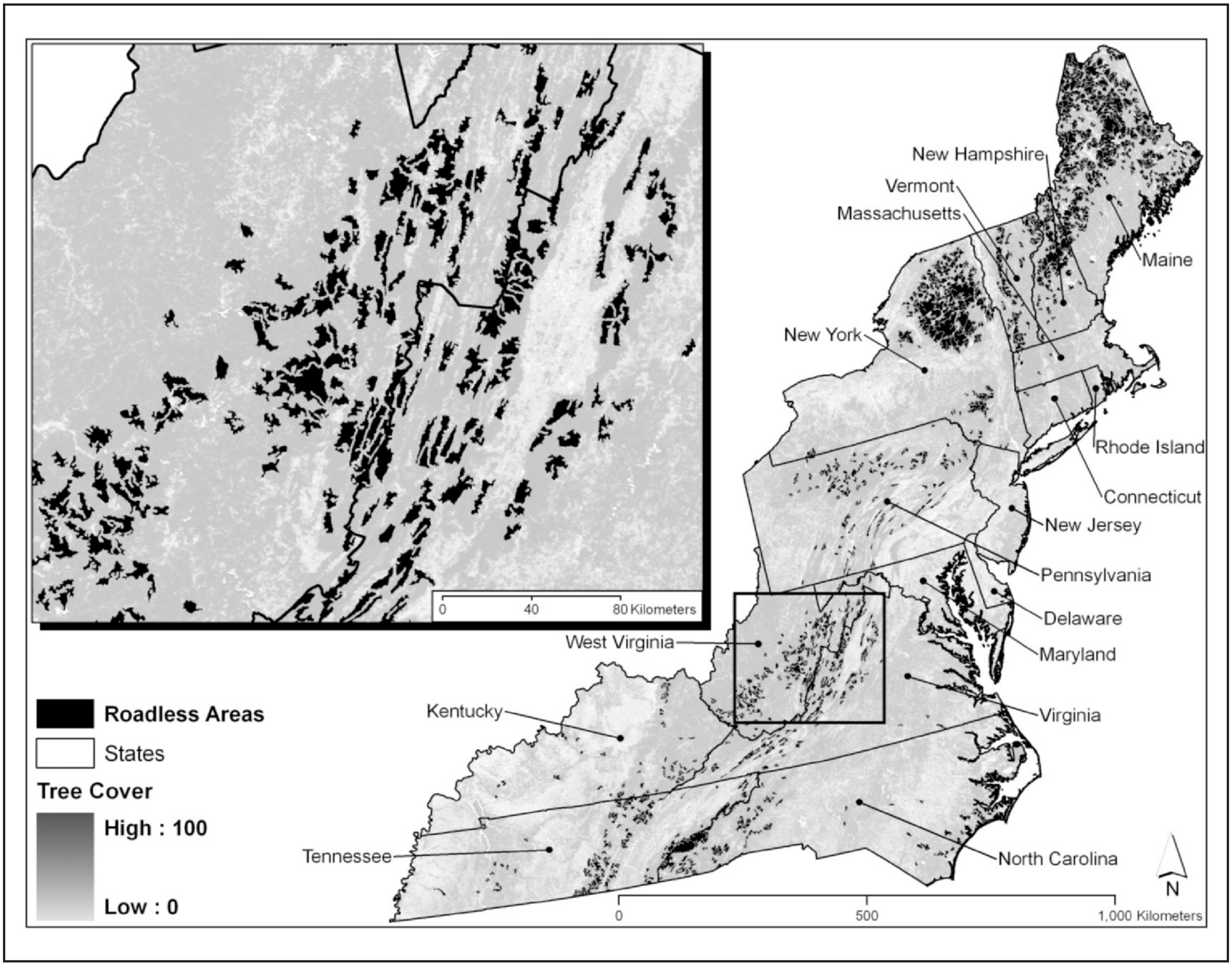

Figure 1. Remote, roadless areas in the eastern United States identified using a 500m distance from the nearest road.

The areas are distributed heterogeneously across the study region. Large numbers of areas lie in northern and western Maine and extend south into New Hampshire where large core areas are contained within the White Mountains National Forest. An irregular strip of core areas extend along the north-south axis of Vermont, many of which are contained within the Green Mountains National Forest. Significant areas are also contained within the Great Smoky Mountains National Park in Tennessee. The Adirondack and Catskill State Parks in New York contain relatively isolated clusters of core areas, as do mountainous areas of Pennsylvania and the ridge and valley physiographic province. The remaining core areas are sparsely distributed across the study area, mostly along the ridges of the Appalachian Mountains. The three largest areas are contained within the Adirondack State Park of New York.

Landscape configuration metrics derived from the baseline case varied widely from state to state across the study region (Table 3). The number of core areas per state range from just one in Delaware to 290 in Maine. Some areas were split across state lines, which increased the number by 150 over the 1177 areas initially calculated over the study area. Median core area size ranged from 45 km^2 in Maine to 13 km^2 in New Jersey.

Alternative Derivations

Unimproved roads had a large effect on the identified core areas (Figure 2a). Excluding areas containing unimproved roads decreased the extent of core area we identified by 16%. Consideration of unimproved roads had different effects across states (Table 4a). For example, West Virginia experienced a 46% decrease in identified core area while North Carolina had a 10% decrease despite comparable initial amounts of 5625 km^2 for West Virginia and 4933 km^2 for North Carolina (Table 2, 500 m buffer, Unimproved Roads).

Increasing the buffer depth from 500 m to 800 m decreased the extent of core area

Table 3. Core area landscape metrics for the baseline case, by state.

	Baseline Case				
State	Number of Patches	Largest Patch (km^2)	Median Area (km^2)	Mean Area (km^2)	Perimeter / Area Ratio
Maine	290	826	45	80	13
Vermont	61	249	42	57	18
New York	142	1,932	40	103	19
New Hampshire	70	466	34	68	22
Tennessee	122	264	32	47	19
North Carolina	110	533	29	45	22
Pennsylvania	132	107	29	32	19
West Virginia	156	235	29	36	24
Virginia	138	157	28	33	25
Delaware	1	26	26	26	13
Kentucky	77	61	23	22	33
Massachusetts	13	33	20	17	27
Maryland	4	31	14	15	44
Connecticut	9	24	13	13	78
New Jersey	2	21	13	13	27
Rhode Island	0	0	0	0	0

identified by 40%, an even larger effect than the exclusion of areas containing unimproved roads (Figure 2b) (Table 4b). On a state basis, decreases in the extent of core area as buffer depth increased corresponded roughly with the total number of core areas in each state.

Removing the tree cover threshold of 60% increased the amount of core area identified in the study area by 5% (3333 km^2) over the baseline case. Some states experienced much greater increases than others. North Carolina and Maine increased more than 700 km^2, although the proportional increase in North Carolina was greater (16% versus 3%). New Jersey had the largest proportional increase in core area (1382%), corresponding to 349 km^2.

Management – Conservation Status

Roughly 20% of core area (17,178 km^2) is currently protected from development and has strong land use controls (i.e., GAP category 1 or 2 lands) (Table 5). The greatest proportion of core area, 42%, was in category 3 lands. Notably, almost 80% of core areas are subject either to development or management activities that could modify or degrade habitat quality.

New York, Pennsylvania, and North Carolina contained the greatest amount of fully protected (category 1 or 2) core area (Table 6). As a percentage within each state, New York and New Hampshire ranked highest, although absolute core area in New Hampshire was comparatively small. Maine, which had the greatest overall amount of core area, had one of the lowest proportions in terms of protected lands.

Analyzing by management category artificially divided contiguous core areas. For example, a single core area may fall under three management regimes. In this case, metrics were calculated on portions of the core areas, which reflect ownership configuration rather than ecological configuration. Category 4 lands, with 6796 core areas, contained 5010 more areas than category 3 lands and 5616 more than category 1 and 2 lands (Table 7). Mean core area was lowest for category 4 lands as well, at 4 km^2. Mean area was highest for category 3 lands (17 km^2) and lowest for category 1 and 2 lands (15 km^2). Perimeter area ratio was highest for category 4 lands and lowest for category 3 lands. These values were much higher than those calculated on a state basis.

The effect of including unimproved roads in the derivations of wild areas was most pronounced in category 4 lands, which decreased by 25%. Reductions in category 1 and 2 lands were 9% versus 12% in category 3 lands. As with unimproved roads, decreasing buffer depth affected

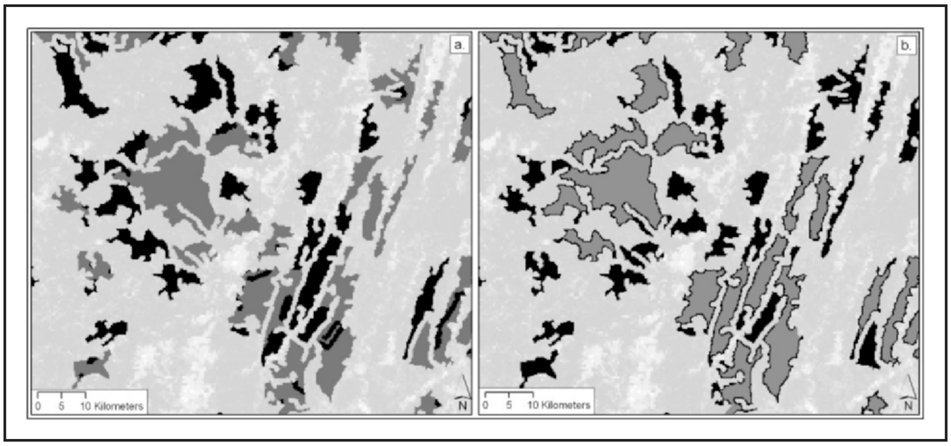

Figure 2. (a.) Effect of unimproved roads on roadless area identification. Black indicates areas added when unimproved roads are allowed in roadless areas. (b.) Effect of buffer depth on roadless area identification. Black indicates areas added when buffer depth is decreased.-

category 3 lands more than category 1 and 2 lands. For the baseline case, increasing the buffer depth in category 1 and 2 lands decreased core area identified by 26%. In category 3 lands, the decrease was 34%. The largest decrease, 55%, again occurred in category 4 lands. Increasing buffer depth had a larger effect when core areas containing unimproved roads were excluded, presumably because the remaining areas were more fragmented. Modifying the tree cover threshold led to minor changes in the amount of core area in each management category. Removing the tree cover threshold of 60% increased the amount of core area identified in category 1 and 2 lands by 3%, in category 3 lands by 4%, and in category 4 lands by 9%.

Connectivity and Case Study

The betweenness metric was not coherently distributed across the study area, but a major corridor was apparent running north/south through Maine and New Hampshire (Figure 3), indicating high levels of landscape permeability in the region. A similar, although less apparent, corridor was evident in West Virginia. Mean betweenness values were highest for category 3 and lowest for category 4 lands.

Core areas in the central part of the study area had higher values of the closeness metric, indicating greater clumping of core areas than to either the north or south (Figure 4). Category 3 lands had the lowest closeness values, while values for category 1 and 2 as well as category 4 lands were comparable. Larger, centrally located core areas had higher values of the degree metric than peripherally located areas, indicating greater node connectivity. Degree values were highest for category 1 and 2 and lowest for category 4 lands.

We identified a 1905 km^2 corridor connecting large core areas in Adirondack State Park with those in Vermont and New Hampshire (Figure 5). The corridor contains high tree cover (68%) but relatively high road densities (1.29 km/ km^2) that may impede dispersal of species like wolves. Impervious surface cover was low, although the corridor is primarily unpro-

Table 4. (a) Change (decrease) in roadless area identified for each buffer width after excluding unimproved roads. (b) Change (decrease) in roadless area identified for each unimproved roads scenario after increasing buffer depth.

(a) Excluding Areas Containing Unimproved Roads

State	500 m buffer Area	500 m buffer Percent	800 m buffer Area	800 m buffer Percent
Connecticut	32	53	0	0
Massachusetts	105	48	2	3
West Virginia	2,601	46	1,233	55
Virginia	1,286	28	671	36
Kentucky	416	24	174	49
Tennessee	1,346	23	734	26
Vermont	575	17	478	23
Pennsylvania	667	16	256	17
New York	1,715	12	1,650	15
North Carolina	504	10	352	12
New Hampshire	429	9	295	9
Maine	1,983	9	1,708	10
Maryland	1	2	0	0
New Jersey	0	0	0	0
Delaware	0	0	0	0
Rhode Island	0	0	0	0
Total	11,658	16	7,552	17

(b) Increasing Buffer Depth from 500m to 800m

State	Unimproved Roads Area	Unimproved Roads Percent	No Unimproved Roads Area	No Unimproved Roads Percent
Connecticut	61	100	28	100
Delaware	26	100	26	100
New Jersey	25	100	25	100
Kentucky	1,374	80	1,131	86
Massachusetts	166	76	63	56
Maryland	40	68	39	67
Pennsylvania	2,773	65	2,363	66
West Virginia	3,371	60	2,003	66
Virginia	2,722	59	2,108	63
Tennessee	2,952	51	2,340	53
North Carolina	2,058	42	1,905	43
Vermont	1,432	41	1,335	46
New Hampshire	1,479	31	1,345	31
Maine	6,800	29	6,525	31
New York	3,737	26	3,673	28
Rhode Island	0	0	0	0
Total	29,016	40	24,910	40

Table 5. Management status of roadless areas (km^2) considering the influence of differing buffer zone depths and unimproved roads (see section 2.3).

	500 m buffer				800 m buffer			
	Unimproved Roads		No Unimproved Roads		Unimproved Roads		No Unimproved Roads	
GAP Status	Area	Percent	Area	Percent	Area	Percent	Area	Percent
Category 1 or 2	17,178	23	15,562	25	12,645	29	11,233	31
Category 3	30,831	42	27,219	44	20,238	46	17,596	48
Category 4	25,360	35	18,931	31	11,471	26	7,973	22
Total	73,370	100	61,711	100	44,354	100	36,802	100

tected (83% in GAP category 4) and thus subject to possible development.

DISCUSSION

Core Areas, Management Status, and Alternative Derivation Scenarios

In the baseline scenario, 73,370 km^2 of core area were identified in the eastern United States. For perspective, there is a total of 4821 km^2 of USFS inventoried roadless areas in the study area and a total of 48,576 km^2 of land in GAP category 1 or 2 status. Thus, compared to the current reserve network, there is a considerable amount of roadless, forested core habitat in the eastern United States. The extent of core area identified is sensitive to assumptions made about different road types and how far their influence extends from the road edge. In our most restrictive scenario, using an 800 m buffer depth and allowing no unimproved roads, the extent of area identified dropped by half (to 36,802 km^2).

The extent of identified core area was also dependent on the data sets used. At a scale of 1:100,000 it is possible that roads were missed in the digitizing process. In a comparison of roads data sets for Northern Wisconsin, Hawbaker and Radeloff (2004) found that road densities calculated using the TIGER 2000 data set were less than half those calculated from digitized DOQQS, with most of the difference due to omission of smaller roads. It is likely that many small paved and unimproved roads present in our study area were not represented in the data set, which would lead to an overestimate of the extent of core areas and an underestimate of the effect of unimproved roads on core area identification. In the absence of regional accuracy assessments for the TIGER 2000 data set, the magnitude of the effect is currently difficult to assess, although most omitted roads would be unimproved (addressed in our scenario assessment).

The management regime for core areas varies considerably. Over a third of core areas are in management regimes that offer no specified legal protection. Another 42% are protected from conversion but subject to activities that degrade the quality of biological resources (e.g., commercial logging). Thus, close to 80% of the core areas identified are subject to uses which may decrease their contribution to conservation of biodiversity. These proportions vary from state to state. Most of New York's core area (70%) was in category 1 or 2 lands, whereas 90% of Maine's was in category 3. West Virginia's core areas were almost evenly split between category 3 and 4 lands, with only a small fraction more fully protected. Because private lands were not systematically surveyed for development of the Protected Area Database (Loucks et al. 2003), we have likely underestimated the extent of protected core area on private lands.

Removing the 60% tree cover threshold as a criterion for inclusion as a core area had less effect on the alternative derivation scenarios than expected, increasing the area identified by just 5%. This result indicates that relatively few of the identified areas were open vegetation types, such as marshes, where tree cover is perennially low. Conversely, it indicates that most of the core areas in the East already have high densities of tree cover (thus would, under most definitions, be described as forest), although the condition of these forested areas likely varies based on allowable land uses. On category 3 and 4 lands in particular, one might expect to find evidence of recent anthropogenic disturbance. Depending on the scale and type of disturbance (e.g., whether clearcut logging or selective harvesting), the impact may not be great enough to decrease average cover in a particular core area below the 60% threshold. This is true in West

Table 7. Core area metrics for each GAP land management category.

Baseline Scenario				
Gap Category	Number of Patches	Mean Patch Area (km^2)	Median Patch Area (km^2)	Mean Perimeter Area Ratio
1 & 2	1,180	15	0.9	75
3	1,786	17	1.4	68
4	6,796	4	0.2	100

Virginia, for example, where selective harvesting of valuable hardwoods like cherry (*Prunus* spp.) and oak (*Quercus* spp.) has accelerated in recent years and where inclusion of unimproved roads in our database is likely underestimated.

Another issue arises when management alters seral stage or forest type. For example, native hardwood forests on the Cumberland Plateau in Tennessee are being clearcut and replanted with non-native pines (McGrath et al. 2004). Our analysis does not distinguish between non-native plantations and native forest stands, although they function differently ecologically and could significantly alter the conservation value of affected core areas.

In light of the variety of datasets used in this study, attention to the influence of scale was required. All data sets were referenced to a master extent and all calculations were made using a 250 m cell size. This required assumption of a uniform within-cell distribution of tree and impervious cover, and resulted in supersampling of the coarser resolution data. However, cover values were averaged; therefore, we expect any supersampling effects to be small and primarily at the edges of core areas.

Using a resolution of 250 m to create the road density data set allowed us to capture finer details of the space between roads. In some cases, this resulted in irregular core areas with spurs and "bottlenecks." The resolution of the impervious surface and tree cover maps could, in some cases, be larger than these spurs and bottlenecks. Because we calculated tree and impervious surface cover at the patch level, we do not expect systematic error in our estimates of cover for core areas.

Higher resolution impervious and tree cover data sets derived from Landsat 30 m imagery are currently available for the coterminous U.S., although we hesitate to speculate how our results would change using higher resolution data. Higher spatial resolution enables identification of finer scale features in the landscape, but the spectral resolution of MODIS is superior to Landsat and the difficulty of detecting low levels of imperviousness with

Table 6. Management status of roadless areas by state, for the baseline scenario, showing percent of roadless area (km^2) under each management type (GAP Status).

GAP Status	Category 1 or 2			Category 3			Category 4		
State	Area	Percent of State Area	Percent of Roadless Area	Area	Percent of State Area	Percent of Roadless Area	Area	Percent of State Area	Percent of Roadless Area
New York	8,614	7	70	325	0	3	3,443	4	28
New Hampshire	713	3	18	2,050	9	53	1,119	21	29
Pennsylvania	2,144	2	72	148	0	5	705	4	24
Vermont	405	2	15	1,308	5	50	912	1	35
North Carolina	1,817	1	44	1,737	1	42	601	1	14
Maine	1,104	1	5	19,856	24	90	1,034	8	5
Tennessee	1,107	1	29	1,321	1	34	1,436	2	37
Virginia	783	1	23	2,052	2	60	592	1	17
West Virginia	323	1	10	1,389	2	44	1,422	1	45
Kentucky	123	0	15	482	0	61	188	1	24
New Jersey	17	0	77	5	0	23	0	0	0
Maryland	15	0	34	28	0	65	0	0	1
Connecticut	6	0	59	5	0	41	0	0	0
Massachusetts	7	0	6	103	0	79	19	0	15
Delaware	0	0	0	24	0	100	0	0	0
Rhode Island	0	0	0	0	0	0	0	0	0

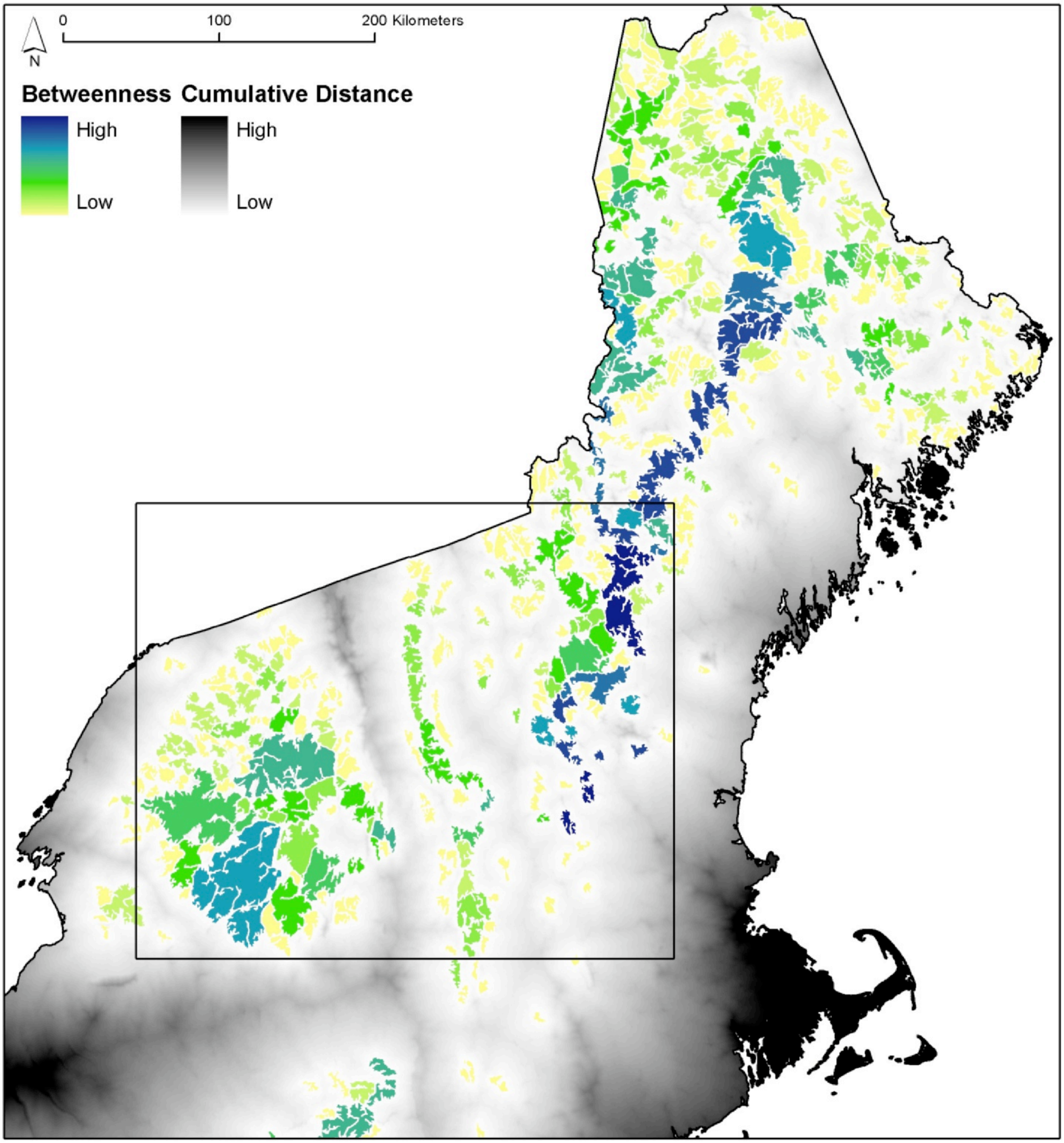

Figure 3. The 'betweenness' connectivity metric for a portion of the study area, focused on New England, with a cumulative cost surface (described in section 3.2) shown in the background (grayscale). Betweeness values range from yellows (low) to blues (high). The high values running through the center of the region indicate a high density of least cost paths traversing those habitat patches. The outlined area depicts that analyzed in Figure 5.

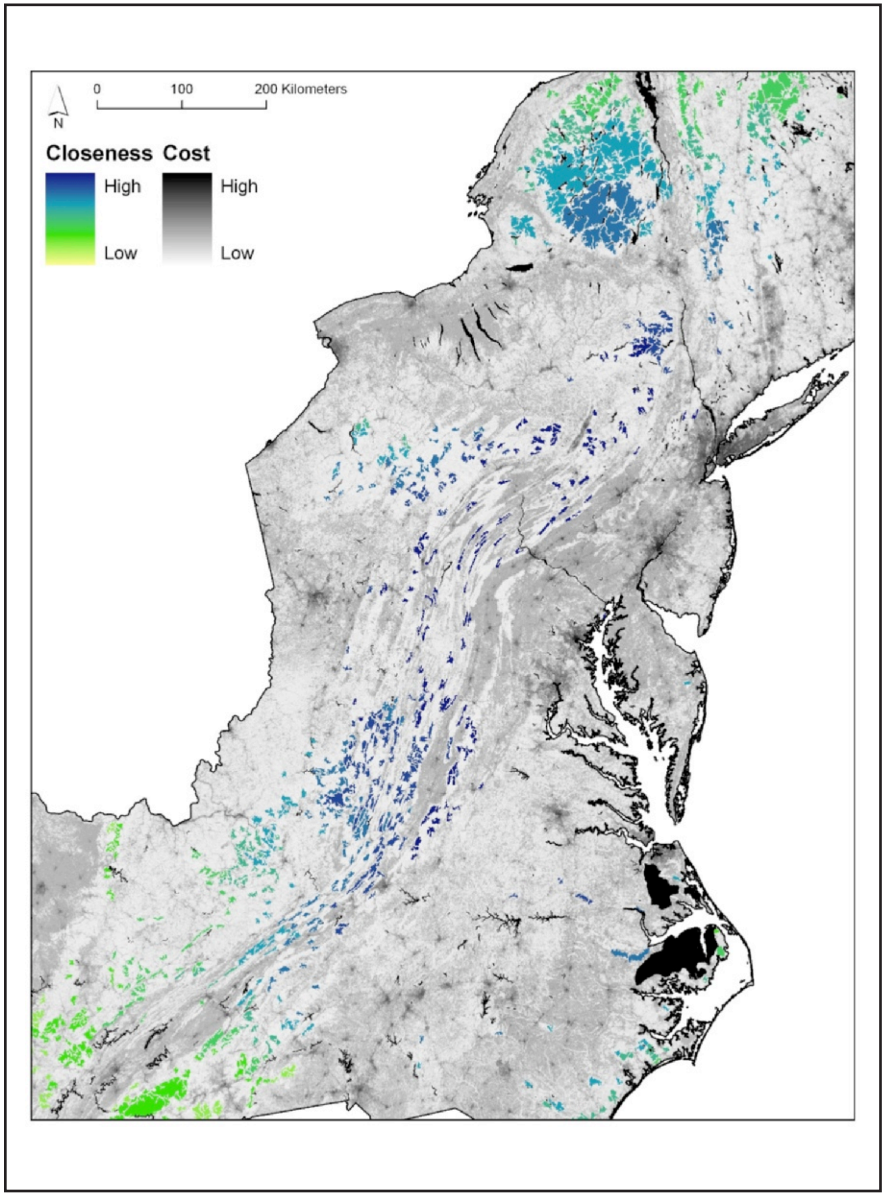

Figure 4. The ‘closeness’ connectivity metric for a portion of the study area, focused on the central Appalachian mountains of Pennsylvania, with the background cost surface (grayscale). Values range from yellow to blue as per figure 3. The core areas in this region have high values reflecting their key role as nodes that have the potential to connect habitats of New England to the southern Appalachians.

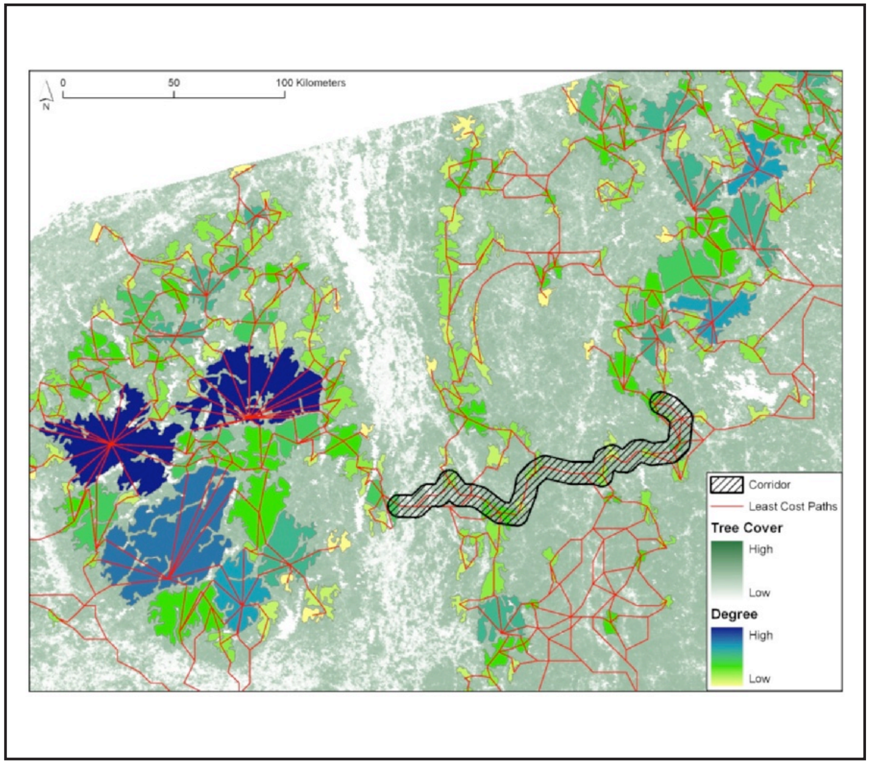

Figure 5. Regional analysis of connectivity between forests in the Adirondacks of New York to core hubs in Vermont and New Hampshire. The ‘degree’ connectivity metric is shown, with values ranging from yellows (low) to blues (high), and a background cost surface (grayscale). Major least cost paths are overlaid as red lines, showing primary connectivity routes derived using the graph theory approach. A corridor (cross hatching) centered on least cost paths was identified as critical for maintaining connectivity between larger clusters of core areas.

the Landsat sensor are well known. The "nighttime lights" data set may, therefore, be more appropriate for detecting diffuse low-density development likely to occur near core areas and, at the scale of this study, the MODIS data are well suited to consistently mapping landscape patterns of canopy density.

Landscape Context and Connectivity

Most core areas were clustered in the northeastern portion of the study area, with Maine alone containing 25% of the total. Maine's core areas were also the largest, with a median size of 45 km^2. The largest core area in the study area was in Adirondack State Park (1932 km^2). The effect of large core areas on statistical summaries by state can be seen in the difference between median and mean areas. For example, median core area size in New York was 40 km^2 while mean core area size was 103 km^2. In general, the largest core areas were associated with national or state parks and forests. An exception were the large industrial forests of Maine, which have undergone tremendous changes in ownership (over 11,000 km^2 in the period 1994 to 2005) and parcelization that will determine the future of conservation in the region (Hagan et al. 2005). The recent trend towards more owners and smaller parcels in Maine and other states across the Eastern U.S. where large timber companies are divesting their lands is likely not reflected in our data sets. For example, real estate investors, part of the new array of land owners in Northern forests, may hold land for several years before conditions are profitable for development, whereupon decreases in canopy cover and increases in imperviousness would become apparent in remotely sensed data. In many cases, new owners are less likely to engage in activities to promote biodiversity. Negative effects on habitat and biodiversity stemming from shifts towards less sustainable management (e.g., declining to obtain forest certification) have been observed (Hagan et al. 2005).

No strong pattern was found in perimeter area ratio values at the state level. Core areas in Maine had some of the lowest perimeter area ratio values, indicating relatively regular patch edges compared to those in West Virginia, for example. The highest perimeter area ratio values were in states with relatively little core area. There were interesting differences between management categories, however. Category 4 lands generally consisted of a large number of small patches, leading to high perimeter area ratios. Unexpectedly, category 3 lands comprised larger patches with lower perimeter area ratios than category 1 and 2 lands. This was likely due to the large, extensive core areas in Maine.

Connectivity measures varied widely across the study area between metrics. Betweenness values were highest for a linear set of core areas in Maine and New Hampshire, indicating low resistance to dispersal in the region. Closeness values were highest in the central part of the study region, a pattern similar to what one would expect when measuring average Euclidean distance between core areas. Degree values were highest for large, centrally located core areas. Some core areas in the Northeast had both high betweenness and degree values, indicating their importance for both local and regional connectivity.

Case Study of a Keystone Predator

Our analysis of core area connectivity in the northeast, using the gray wolf as a focal species, illustrated the utility of the graph theoretic approach for conservation planning. Other applications of the approach have focused on theoretical species (Bunn et al. 2000) and caribou (*Rangifer tarandus*) (O'Brien et al. 2006). The Wildlands Project and Defenders of Wildlife have identified forested areas in Maine and the Adirondacks suitable for supporting wolf populations but future development could reduce suitability if connectivity between core areas decreased, impairing the ability of large areas (such as Adirondack State Park) to sustain viable wolf populations without dispersal from areas to the northeast.

We identified one possible corridor for wolves dispersing between forests in Maine and the Adirondacks. Road density in the corridor is higher than that tolerated by wolves in their home ranges, for which the upper threshold ranges from 0.45 to 0.58 km/km^2 (Thiel 1985; Mech 1989; Mladenoff et al. 1995). However, adjacent areas of high quality habitat can increase the tolerated road density to ~0.7km/km^2 (Fuller et al. 1992), and dispersing wolves will travel across considerable distances of unsuitable habitat (including major roadways) to reach favorable habitat (Mech et al. 1995). Nonetheless, the probability of successful dispersal decreases as human associated mortality risk increases (Shepherd and Whittington 2006). The high tree cover and low level of development in the corridor we identified indicates limited dispersal may currently be possible, although protection and restoration of critical areas would increase the likelihood of its success. This example reveals aspects of the landscape important for wolf dispersal, and the approach could be tailored to other species or systems. For example, riparian corridor connectivity could be measured using highly detailed land cover maps incorporating vegetation density and structure within specified buffer distances from streams (Goetz 2006).

CONCLUSION

Development pressures that threaten core habitat and connectivity are intensifying in much of the nation and extending far beyond urbanized areas in the form of rural residential development and second home building. Some of the highest rates of exurban development in the country are occurring in Eastern temperate forests, particularly New York, New Hampshire, Vermont, and Maine. If current trends continue, increased fragmentation and conversion by exurban development of many of the core areas we identified is likely, particularly because 80% remain unprotected. Not only would this be an important loss of habitat area, but would further fragment and isolate habitat islands, decreasing successful dispersal and increasing the likelihood of local species extinctions.

Our results suggest a starting point for the construction of a more comprehensive reserve network for the study region and can also aid broader ecological research, including the national ecological observatory network (NEON) requirement for core wildland areas as remote measurement sites. Acquiring or negotiating development rights for remote areas on private lands, and increasing the number of designated wilderness areas on public lands for incorporation into a larger reserve network, would facilitate the preservation of remaining core habitat, associated biological diversity, and keystone species. Because many of the data sets we used are available nationwide, similar analyses could be conducted to assess the extent and status of core areas across other regions.

While our results highlight important issues facing core areas in the east, they underscore important issues of data quality and completeness when conducting large scale assessments. For example, improved road data could alter the results of the analysis presented here. If roads were omitted primarily at patch edges, many smaller patches would be eliminated, leading to higher mean and median patch areas. If roads were omitted internal to patches, elimination of small areas could be offset by splitting of larger areas, leading to no net change or even decreases in mean and median patch area. Perimeter-area ratio could decrease if many small patches were eliminated or increase if the splits of large patches offset small patch loss. We would expect the largest effects in GAP 3 and private lands where smaller roads for timber extraction are more common.

A more current database of protected areas could also alter our view of the status of core areas. Many NGOs in the Eastern United States, notably The Nature Conservancy and the Wildlands Project, are currently working on the protection of large parcels (hundreds of thousands of hectares), much of it forested, via conservation easements, management agreements, or fee simple acquisitions. Thus, while our results do not reflect the current extent of private lands protected from development, they do emphasize the contribution private lands can make to the current reserve network.

ACKNOWLEDGMENTS

We acknowledge support from Woody Turner via the NASA Applied Sciences Program (Ecological Forecasting), and we thank Ben Best for his assistance with the habitat modeling toolbox he developed at Duke University. We also acknowledge the assistance of Greg Fiske, Dan Steinberg, and Claire Jantz with data set processing.

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