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Projecting transition probabilities for regular public roads at the ecoregion scale: A Northern Appalachian/Acadian case study

Robert F. Baldwin[a,*], Stephen C. Trombulak[b], Mark G. Anderson[c], Gillian Woolmer[d]

[a] Two Countries, One Forest, 6151 Allan Street, Halifax, Nova Scotia B3L 1G7, Canada
[b] Department of Biology and Program in Environmental Studies, Middlebury College, Middlebury, VT 05753, USA
[c] The Nature Conservancy, Eastern Resource Office, 11 Avenue De Lafayette, Boston, MA 02111, USA
[d] Wildlife Conservation Society Canada, 720 Spadina Avenue, Suite 600, Toronto, Ontario, Canada M5S 2T9

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Abstract

Existing roads have far-reaching effects on biodiversity, and therefore road network expansion is of critical concern to conservation planning. Road density trend analysis is often too coarse and assumes homogeneous landscapes, whereas spatial transition probability analysis captures landscape variability typical of ecoregions. Simple models for projecting road network growth will assist planning agencies and conservation organizations to guide protection efforts. We investigate growth of regular public roads in the State of Maine over a 17-year historical period, and then use the best-selected (AIC) logistic regression model to validate and then project spatial probability of future roads to the Northern Appalachian/Acadian ecoregion. Nearly 2000 km of new roads were constructed in settled landscapes in Maine 1986–2003, influencing 37,000 ha of adjacent habitats. The majority (93.5%) of the new roads performed local functions and were short (<1/3 km in length), characterized as residential roads typical of sprawl. The best-selected logit model [dwelling density (+), elevation (−), distance to urban area (−), distance to existing primary/secondary highway (−)] captured 84% of reserved new road points in Maine, and only 27% of random points at the >0.5 probability level. The projected model forecasts 0.5 million km of new residential public roads in the Northern Appalachian/Acadian ecoregion for the next two decades, suggesting that cumulative effects of residential road network expansion are a serious region-scale biodiversity threat.

Keywords: Ecoregion; Conservation planning; Road networks; Sprawl

1. Introduction

Road networks influence biodiversity at local to continental scales (Ritters and Wickam, 2003). Because road systems introduce human activity to ecosystems and facilitate the conversion of habitat and removal of natural resources, being able to forecast their expansion can be a valuable tool for conservation planning (Laurance et al., 2001). Roads have multiple biogeochemical effects (reviewed by Saunders et al., 2002; Trombulak and Frissell, 2000) affecting ecosystems as much as 1 km away (Forman and Deblinger, 2000). As a filter to movements, roads pose major threats to wildlife, including wide-ranging large mammals (Kramer-Schadt et al., 2004; Philcox et al., 1999). Severe population level impacts have been recorded for small or slow-moving animals, including reptiles (Bernardino and Darlrymple, 1992; Gibbs and Shriver, 2002), amphibians (Fahrig et al., 1995; Hels and Buchwald, 2001) and small mammals (Caro et al., 2000; Haskell, 2000). High mortality and other barrier effects (e.g., avoidance) lead to population isolation and inbreeding (Hitchings and Beebee, 1998; Reh and Seitz, 1990). Of pressing concern for protected areas management, roads provide corridors for invasion of exotic species (Parendes and Jones, 2000) and expanding human access (reviewed by Forman et al., 2003). When road system expansion can be reliably forecast at ecoregional scales, a host of future human impacts may be assessed (e.g., Laurance et al., 2001), helping to prioritize conservation action based on threat (Abbitt et al., 2000; Theobald, 2003).

* Corresponding author. Tel.: +1 864 654 4135.
E-mail addresses: robert.baldwin@2C1Forest.org (R.F. Baldwin), trombulak@middlebury.edu (S.C. Trombulak), manderson@TNC.ORG (M.G. Anderson), gwoolmer@wcs.org (G. Woolmer).

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Responding to the increasing rate of environmental degradation and biodiversity loss, conservation planning has expanded from small and local scales to the assessment of large ecological regions (Groves et al., 2002). At these scales planning is greatly aided by a systematic understanding of both the biological values present and the looming threats from human development (Margules and Pressey, 2000). While urban planning has long been concerned with how road networks grow (Yamins et al., 2003), little has been accomplished in forecasting regular public road expansion in areas where large-scale conservation projects may still happen, such as the largely rural and forested landscapes of the Northern Appalachian/Acadian ecoregion. Road density (e.g., km road/km^2) is a reliable, easily obtained metric used to assess and anticipate ecological effects; however, it is best applied when the spatial distribution is regular across the extent of the study area, and when broad resolutions (i.e., 1 km^2 blocks) are acceptable (Saunders et al., 2002). At the ecoregion scale, geographic variation in density of roads is often pronounced and may be due to underlying geographic patterns (e.g., elevation, proximity to settlement). To forecast at the ecoregion scale in a manner that can be readily applied by conservation planners, we need tools to predict transition probabilities for landscape change that may be projected over vast landscapes using readily available geographic data (Soares-Filho et al., 2001; Theobald, 2003). Transition probabilities set a time-dependent probability that a portion of the landscape (i.e., a raster cell) will undergo transition from one land use to another, useful in calibrating the urgency of conservation action (Bell and Irwin, 2002; Soares-Filho et al., 2001).

With rapid urbanization of rural landscapes, new public road construction is often associated with "sprawl"—unplanned, low-density residential development that cumulatively transforms rural into "exurban" landscapes (Gutfreund, 2004; Theobald, 2004). Large highways have the most dramatic landscape effects, but the vast network of local roads (i.e., primary and secondary roads in rural landscapes) can accumulate through time and space and ecologically impact more area (Forman, 2000). Much of the United States' system of primary and secondary highways and interstates was built in order to stimulate future economic growth (Seely, 1987), and stimulating growth is still the reason for planned highway expansions in much of the developing world (Fearnside, 2002). However, most road systems in rural areas of North America today grow in order to meet rising transportation demands (Forman et al., 2003). New road spurs are built to access residential developments, and arterials arise when transportation demands exceed the capacity of existing highways (Yamins et al., 2003). It is these landscapes outside of urban areas that are at the leading edge of transition from traditional land uses to residential housing (Bell and Irwin, 2002) and where habitats are most at risk from the effects of permanent land-use conversion (Theobald, 2003). Being able to forecast hotspots of road growth over vast landscapes would be a valuable asset for ecoregional conservation planning.

The Northern Appalachians/Acadian ecoregion has been a focus of conservation planning for The Nature Conservancy, The Wildlands Project, Wildlife Conservation Society and numerous local groups for more than a decade (Anderson, 1999; Bateson, 2005; Bley et al., 1994; Carroll, 2005). With millions of hectares of undeveloped private forests, undeveloped shorelines, and spectacular wilderness vistas within a day's drive of several large urban centers (i.e., Montreal, Quebec, Boston, New York City), the Northern Appalachians/Acadian ecoregion is ripe for increased settlement (Alig et al., 2004; Plantinga et al., 1999; Trombulak and Klyza, 1994). For conservation planning in the region, there is a strong need to understand potential future development patterns. One way to forecast how future networks of secondary rural roads will expand is to use a logit-based approach to derive transition probabilities from geographical data. Projecting transition probabilities for components of the road network (i.e., public or private roads) is a necessary step towards assessing regional threats and prioritizing regional conservation action. When using a logit approach (Agresti, 1996), the best-selected model can then be included in simulation models projecting the future extent of new roads as represented in a probability map.

In this study, we develop an approach to forecast the growth of a class of roads using historical data to project transition probabilities over an entire ecoregion. We explore the formation of new regular public roads (which we define as public roads not on public lands) in the State of Maine, U.S.A.—a subarea of the Northern Appalachian/Acadian ecoregion, develop and validate an explanatory model, and demonstrate its projection for an ecoregion. The available historical data set spans a 17-year period, providing a basis for forecasting trends over a similar (i.e., 20-year) time scale. The application of the method will be for threat forecasting in landscape-scale conservation planning. In order to make our process generalizable to other ecoregions, we use spatially explicit data that are available at low cost for most of the planet.

2. Materials and methods

2.1. Study area

The Appalachians of North America stretch from northern Georgia to the tip of the Gaspé Peninsula (Brooks, 1965). Because of proximity to eastern cities, this mountain chain is undergoing extensive second home development (Nash, 1999; Wear and Bolstad, 1998). The Northern Appalachian/Acadian ecoregion (NAP) encompasses the cool, spruce and hardwood clad, northern extent of the Appalachian Mountains, which along with the marine and coastal influences, have helped to define the ecological history of the Northeast. From the Tug Hill plateau of New York, the ecoregion extends across the Adirondack Mountains, the Green Mountains of Vermont and the White Mountains of New Hampshire, into Maine and including all the provinces of Maritime Canada. It also covers the Appalachian complex of eastern Quebec extending to the Gaspé Peninsula and the Îles-de-la-Madeleine (Magdalene Islands). It is the second richest ecoregion for vertebrate diversity within the temperate broadleaf and mixed forest regions (Ricketts et al., 1999). The geographic boundaries of the ecoregion were derived and modified by an international team of scientists from standard ecological land classification frameworks in Canada and the US (Bailey et al.,

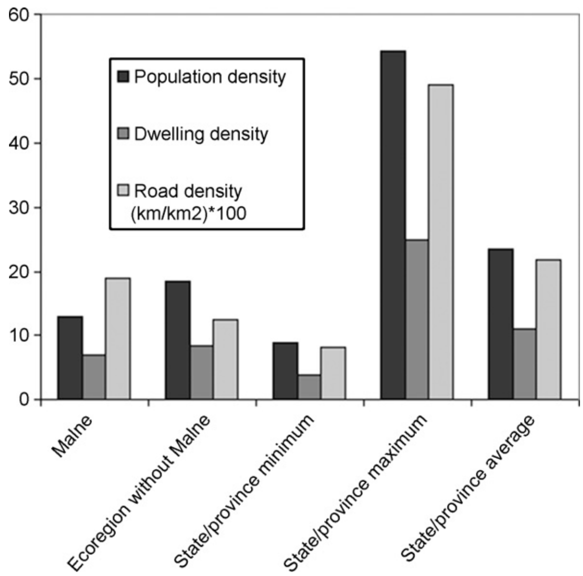

Fig. 1. Comparison of settlement patterns in Maine to the remainder and averages of the whole ecoregion, and extreme values.

1994; ECWG, 2003; Keys et al., 1995; Li and Ducruc, 1999; Marshall and Schut, 1999; Neily et al., 2003; Omernick, 1987).

The State of Maine, U.S.A., makes up 21% of the Northern Appalachians ecoregion, and almost all (98%) of the state falls within the ecoregion plus the 40 km boundary buffer. Maine is in many ways representative of the ecoregion as a whole. It has equivalent settlement patterns, i.e., is more similar to ecoregion averages for population, dwelling and road density than to extremes (Fig. 1). Maine represents the entire elevation gradient present in the ecoregion, from sea level to alpine (the only peak higher than 1605 m Mt. Katahdin in Maine is Mt. Washington in New Hampshire at 1917 m). Likewise, Maine has historical and present economic and cultural connections with neighboring Canadian provinces (Hornsby and Reid, 2005), and U.S. states (Dobbs and Ober, 1995).

2.2. Road networks

The historical network of paved, public roads was defined from line data produced 1984–1986 for the Maine Low-level Radioactive Waste Authority (1:100,000). The current network was defined from data made in 1994–2003 by the Maine Department of Transportation (1:24,000) including functional attributes (arterials, collectors and local), speed limit, jurisdiction (town, state or federal), and annual average daily traffic (number of vehicles per day averaged annually) (http://apollo.ogis.state.me.us/catalog/). The “new roads” dataset was identified by subtracting the historical roads from the current roads. Because the historical and current roads were off register with respect to each other by a few to >50 m, the historical data was buffered to 100 m. A new road is considered to be the segment that occurs between nodes (locations where one or more roads join). For regression analysis, the lines were converted to a 50 m × 50 m grid, and centers of cells with new road presence were then converted to points (N = 29,260 points). For model validation, 50% subsets were randomly extracted to be used as “training” and “test” data sets (Johnson, 2001).

2.3. Model development

A 50 m × 50 m grid was created with water (streams, ponds, rivers and lakes) omitted. From this grid, 15,511 random points on the landscape (equivalent to the number of “new road” points in the “training” data set) were drawn.

Five simple, region-wide parameters that we believed a priori to be associated with road development were assessed at each new road and random point:

(a) Distance to nearest primary and secondary highway (ROADDIST).
(b) Distance to nearest urbanized area (URBDIST, based on their most recent delineation by the U.S. Census (U.S. Census, 2002).
(c) Population density (POPDEN) and dwelling density (DWELLDEN), based on the most recent population and dwelling density of the U.S. Census block (U.S. Census, 2002) upon which the point fell.
(d) Elevation (ELEV), derived from a digital elevation mosaic for the State of Maine.

To determine if new roads were distributed non-randomly over the landscape, spatial dependence of new road points was assessed using Moran’s I. Points containing a new road were assigned a presence value of 1 and random points were assigned a presence value of 0. There was no overlap between random (0) and new road (1) points.

Logistic regression was used to explain the probability that a point was a 1 (new road) based on the attributes of those points (Agresti, 1996). To assess spatial autocorrelation, x and y coordinates were included with other explanatory variables in regression analysis.

Because spatial autocorrelation was present in even greatly reduced versions of the data set (i.e., a random 5% of the points), a rule was sought whereby the number of new road points could be reduced in such a way as to have greatest relevance to the actual spatial distribution of new roads. A total of 1848 km of new roads were in the “new roads” data set, with an average length of 325 m. Thus, 5686 points (1848/0.325 km), or 18.9% (~20%) of the total number of points, are needed to represent one point per average segment length (325 m) of new road. To increase average distance among points to approximate this ideal density, a random 20% of the data set was used. Because the data set was halved into training and test subsets, 40% of the training subset was used to build the model (response profile: 1 = 5835, 0 = 6165).

To build the model, main effects only were included. Stepwise model selection was used (α = 0.05 significance level for inclusion of effects in model) with the AIC value (Burnham and Anderson, 2002) indicating the suitability of the best approximating model compared to previous steps (SAS, Inc.). Fit of the selected model was evaluated using maximum rescaled R^2, concordance (within random data pairs, the correct association of a lower or higher predicted probability with a lower or higher observed response) and the residual Chi-square test (SAS, Inc.).

2.4. Model validation

The ability of the best-selected model to capture reserved actual new road data points was assessed, and compared to its inclusion of random "road" points. The best-selected logit model derived from the "training" portion of the data set was projected back onto the State of Maine as a probability surface. The relative capture of the reserved portion of the new roads and random point data set by the projection was assessed.

2.5. Ecoregional projection

To demonstrate a road forecast using ecoregion-scale data sets, we projected the best-selected model for the Northern Appalachian/Acadian ecoregion. Region-scale data sets for elevation, dwelling density and distance measures were obtained from a larger transboundary conservation planning project (2C1Forest) (Bateson, 2005). Probability projections were assessed for extent and impact [impervious surface and ecological effect zone of 200 m (Forman, 2000) at very high (>0.95), high (>0.90), moderately high (>0.80) and random levels (0.50)]. We tested the assumption that the area of overlap significantly influenced the projection, and found that – based on actual overlapping 200 m effect zones in the current road system – the anticipated area of overlap was 0.5%. Thus, we reduced those projections by that amount.

3. Results

3.1. New regular, public road development in Maine

In total, an estimated 1848 km of new paved, public roads were created in Maine over the 17-year historical period for which data were available (N = 5691 new roads), 5% of the existing 37,243 km of public roads present in 2003.

This is a conservative estimate of extent because (a) buffers applied to historical roads clipped portions of new roads and (b) not all new roads would have yet been recorded in digital form by 2003. Based on a road surface width of 10 m (Reed et al., 1996; Saunders et al., 2002), 18.5 km^2 of impervious surface may have been added by regular public roads built in Maine 1986–2003, an area approximately equal to the 500′ Appalachian Trail corridor in the 100 Mile Wilderness in Maine (24.5 km^2). Adding to this an ecological effect zone of 200 m on either side (Forman, 2000), 739 km^2 of adjacent habitats were affected to some extent, nearly the area of Maine's wilderness crown jewel, Baxter State Park (818 km^2).

Most new roads created in Maine between 1986 and 2003 were relatively short (mean 325 m, S.D. 408 m; Fig. 2), and local in function. According to functional classifications accompanying the data set, the vast majority (93.5%) functioned as local roads, with a modal speed limit of 45 mph (range 25–65). Only 4.8% functioned as major arteries or collectors (1.8% as minor arteries or collectors). According to jurisdiction classifications,

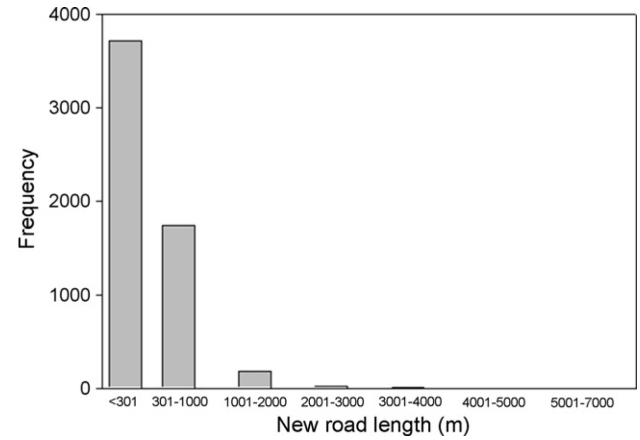

Fig. 2. Frequency histogram of new road segment lengths (regular, public roads) formed in Maine 1986–2003.

87% of the new roads created 1986–2003 were "townways" indicating a high degree of local control in planning, permitting and maintenance. The new roads arising 1986–2003, in addition to being relatively short, show a pattern of being dead ends and cul-de-sacs, typical of new subdivisions (Fig. 3).

3.2. Explanatory model

New paved, public roads were highly clustered in the landscape (observed distance to nearest neighbor/expected distance = 0.05, $Z = -309.7$, $p < 0.01$; Fig. 4), indicating that their occurrence was due to non-random processes and could be modeled.

All variables included in the regression analysis (ELEV, POPDEN, DWELLDENS, URBDIST, ROADDIST) were significantly intercorrelated ($p < 0.001$). Stepwise model selection excluded POPDEN. The ΔAIC value for the best-selected model (10,892.5) versus the nearest candidate model (10,905) was 12.5, exceeding ΔAIC = 2 (Burnham and Anderson, 2002). The best-selected model given the data used in the analysis had a maximum rescaled R^2 of 0.51, concordance over 36 million pairs of 87.1%, and the null hypothesis that the model fit the

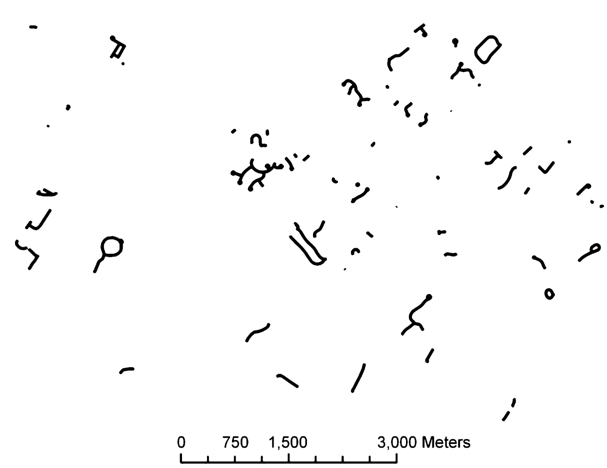

Fig. 3. Representative close-up of new road fragments formed in Maine between 1986 and 2003.

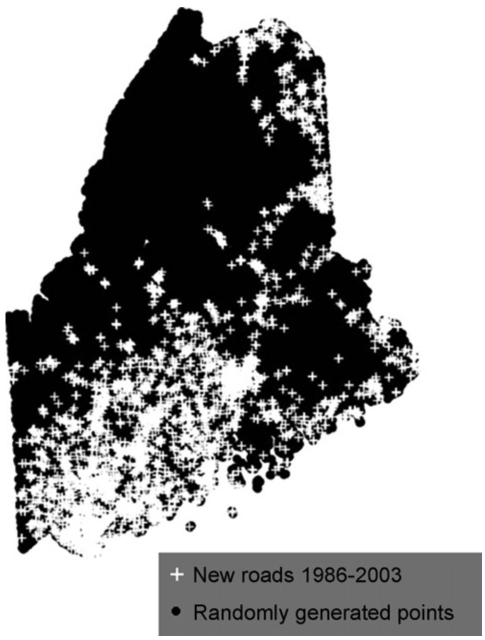

Fig. 4. Distribution of points used to develop explanatory model for road forecast, showing clustered distribution of new roads compared to randomly generated points.

data was not rejected ($X^2 = 0.397$, $p = 0.53$). Parameter values and the logit are as follows:

Probability of new road = exp(1.0646 + (−0.00028 × ELEV) + (0.0158 × DWELLDENS) + (−0.00003 × URBDIST) + (−0.00030 × ROADDIST))/1 + exp(1.0646 + (−0.00028 × ELEV) + (0.0158 × DWELLDENS) + (−0.00003 × URBDIST) + (−0.00030 × ROADDIST)).

3.3. Model validation

The best-selected model produced a probability surface that significantly better predicted the reserved new road points than the reserved random road points. The new road points in the reserve data set had, on average, a probability level of 0.68 (S.D. 0.211), while the random reserved points had on average a probability level of 0.29 (S.D. 0.263) after arcsin transformation ($t = 136.5$, $p < 0.0001$). Most (83.9%) of the reserved new road points had a probability level of ≥0.5, while less than one-third (27.6%) of the reserved random road points were ≥50% likely to occur under the best-selected model.

3.4. Ecoregional projection

According to our forecast for the Northern Appalachian/Acadian ecoregion there is a very high (0.95) probability that nearly 1/2 million new km of residential roads will be built during the coming 17 years (Table 1; Fig. 5). Other forecasted effects may include approximately 80,000 km^2 of ecological effect zone (nearly 10× the area of Yellowstone National Park), and over 6000 km^2 of new impervious surface.

4. Discussion

One of the greatest threats to global biodiversity conservation is the accumulation, over time and space, of incremental expansions of human infrastructure (United Nations Environment Programme, 2002; Vitousek et al., 1997). Roads are one of the most pervasive aspects of global human influence (Sanderson et al., 2002) with multiple biogeochemical effects in the roadways and adjacent habitats, and pose significant threats to movements of wildlife (reviewed by Saunders et al., 2002). The historical pattern of new road formation in Maine 1986–2003 indicates that most new public roads arise through a disaggregated, localized process that will aggregate to widespread cumulative ecological effects. The form and function of the new regular public roads indicate that the majority are local, short (<0.5 km) and arose to service subdivisions, and therefore is most likely a locally controlled process governed by landowner decisions mediated by town government. As we have shown using an available historical data set for a subregion (Maine), the cumulative effect of these incremental additions to the road network is on the order of thousands of new km/region/decade. In the rural State of Maine alone, historical patterns of new residential road growth show 1000 km/decade, and we project several hundred times that level to the ecoregion scale, keeping in mind that this is as yet a rural and "low-density, low-growth" ecoregion (1.9% average county population density growth rates during the 1990s: http://www.census.gov/; http://www40.statcan.ca/l01/cst01/), below the U.S. state 1990–2000 average of 13.1%).

The risk posed by such a diffuse process to biodiversity at multiple scales is significant, as the effects from local-scale road building aggregate to the transboundary, multi-state and province, region-scale. Estimated traffic volume on the 1848 km of new roads created 1986–2003 in Maine was 146,000 vehicles/year (79/km/year). Such an increase is expected to lead to wildlife mortality and other barrier effects

Table 1
Forecasted extent of new roads in the Northern Appalachian ecoregion

Probability	Grid cells (count)	Length new road (km)	Impervious surface (km^2)	Ecological effect zone (km^2)
Very high (≥0.95)	387,385	428,663	4,287	81,446
High (≥0.90)	539,467	596,851	5,970	113,421
Moderately high (≥0.80)	959,199	1,061,409	10,614	201,668
Fifty–fifty (≥0.50)	15,248,962	16,873,851	168,739	3,206,032

Extent of impervious surface is based on an estimated average width of a road of 10 m (Reed et al., 1996); ecological effect zone is based on estimated distance from a secondary road of 200 m (Forman, 2000), and adjusted for overlap.

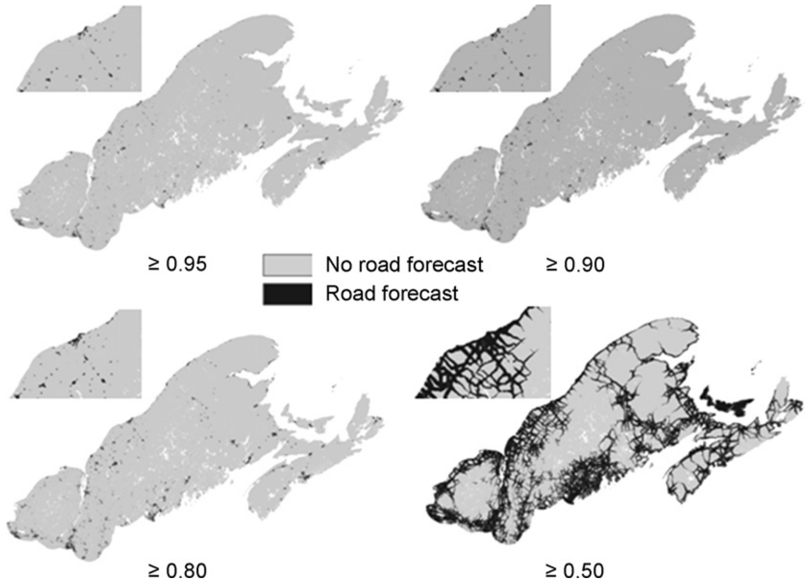

Fig. 5. Forecasted area anticipating new public roads in Northern Appalachians at four levels of probability, with insets showing close-ups.

(Caro et al., 2000). Because primary and secondary local roads of this type in this region have significant negative effects on large-bodied turtle populations (Gibbs and Shriver, 2002), on sex ratios of turtle populations (Steen and Gibbs, 2004) and on migrating amphibians (Fahrig et al., 1995; Findlay and Bourdages, 2000; Turtle, 2000), forecasts using our projection method may be able to assist in mitigating the effects of roads on wetland-dependent fauna, already in global decline (Houlahan et al., 2000). Increased traffic flow on short, residential roads and consequent construction of larger arterials will result in barriers to movement of larger vertebrates (Kramer-Schadt et al., 2004). Some of these species in this region are in delicate stages of recovery [e.g., lynx (*Lynx lynx*), and wolves (*Canis lupus*)]; their eventual success – and maintenance of existing mesocarnivore populations – is in part based on the ability to disperse freely in roadless landscapes (Carroll, 2005; Ray, 2000).

If historical patterns in Maine prevail, the cumulative ecological effect of thousands of new, short (i.e., <0.5 km) roads projected for the region is likely to be severe. The projected model forecasts nearly 0.5 million km of new, residential public roads in the Northern Appalachian/Acadian ecoregion for the next two decades. Conservatively, 80,000 km^2 of terrestrial and aquatic habitats are likewise expected suffer indirect ecological impacts. The area estimate is conservative because the projection uses current estimates of dwelling density, which will increase over time (Wear and Bolstad, 1998). It is possible that the Northern Appalachian/Acadian ecoregion, because of its abundant forested landscapes, undeveloped coastlines and inland lakes, will see rapid amenity-driven changes in dwelling density comparable to other regions of North America (Brown et al., 2005). Even so, the anticipated affected area approaches the extent of the forested area – 120,000–270,000 km^2 – forecasted to be severely degraded due to planned highway expansion in the Amazon Basin (Carvalho et al., 2001). This area is roughly equivalent to 10 Adirondack State Parks (24,300 km^2 each). Ecological effects at this scale need to be taken seriously; when entire ecoregions are substantially influenced by land-use change, even climate can be altered (Dale, 1997).

Our model is region-specific and is limited to one road class (regular public roads). We do not suggest that these specific variables will be the ones driving new public road formation everywhere, e.g., elevation may not be a factor in uniformly flat landscapes. Nor do we suggest that regular public road processes are the same as public lands roads, private forest roads, or major arterials (e.g., interstate highways). The regular public roads model works reasonably well for Maine, and may be projected to the ecoregion as a whole. But, a complete ecoregional road forecast would also need to take into account the other road classes mentioned above. An advantage of our approach – that hopefully will be duplicated for other road classes – is its use of broadly available data sets (i.e., roads, population, dwellings and elevation), enhancing, we believe, its applicability to large scales and other ecoregions. Such coarse-scale approaches for large-scale conservation planning based on roads have been very useful for forecasting spatially explicit threats in the Amazon basin (Carvalho et al., 2001; Fearnside, 2002; Laurance et al., 2001).

Land-use transition of individual ownership parcels from rural to residential is a disaggregated process (Bell and Irwin, 2002), tied to geographic variability (Theobald and Hobbs, 1998; Wear and Bolstad, 1998) and closely linked to the construction of residential roads. Parcel-based land-use transition models are very accurate compared to the aggregated regression model we use for roads here (Theobald and Hobbs, 1998), but are limited by the lack of tax parcel level economic data in most transboundary, forested landscapes. A step in the direction of discretization of land-use change is to develop transition probabilities using logistic regression, with spatial variables extracted from readily available data layers on physiogeographical and census parameters (Soares-Filho et al., 2001). Because roads are one of the major vectors for ecological change (Forman et al., 2003), forecasting future road impacts – especially cumulative impacts at the ecoregion scale – will be useful for anticipating future conservation conditions, where residential expansion threatens to convert habitat away from a more natural state presumably more suitable to support native biodiversity.

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