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

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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).

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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.,