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Tropical deforestation in Madagascar: analysis using hierarchical, spatially explicit, Bayesian regression models

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Abstract

Establishing cause–effect relationships for deforestation at various scales has proven difficult even when rates of deforestation appear well documented. There is a need for better explanatory models, which also provide insight into the process of deforestation. We propose a novel hierarchical modeling specification incorporating spatial association. The hierarchical aspect allows us to accommodate misalignment between the land-use (response) data layer and explanatory data layers. Spatial structure seems appropriate due to the inherently spatial nature of land use and data layers explaining land use. Typically, there will be missing values or holes in the response data. To accommodate this we propose an imputation strategy. We apply our modeling approach to develop a novel deforestation model for the eastern wet forested zone of Madagascar, a global rain forest "hot spot". Using five data layers created for this region, we fit a suitable spatial hierarchical model. Though fitting such models is computationally much more demanding than fitting more standard models, we show that the resulting interpretation is much richer. Also, we employ a model choice criterion to argue that our fully Bayesian model performs better than simpler ones. To the best of our knowledge, this is the first work that applies hierarchical Bayesian modeling techniques to study deforestation processes. We conclude with a discussion of our findings and an indication of the broader ecological applicability of our modeling style.

Keywords: Tropical deforestation; Bayesian statistical hierarchical models; Spatially explicit regression models; Misaligned spatial data; Human population pressure; Land-use classification; Statistical model comparison; Multiple imputation

1. Introduction

The demise of the world's tropical rain forests has been of central concern to conservation biologists for

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at least 20 years (Singh, 2001; Whitmore, 1998). But cognizance of the problem was apparent decades earlier (cf. Jarosz, 1993; Perrier de la Bâthie, 1921). Yet it has proven surprisingly difficult and controversial to obtain accurate estimates of deforestation rates or indeed to relate current forest cover to potential or historical extent of forest cover. This remains true even with the advent of satellite imagery from the 1970s (Apan, 1999). The difficulties arise from issues of definition and benchmarks, spatial and temporal resolution, and data adequacy (Singh, 2001; Angelsen and Kaimowitz, 1999). As a consequence even the most recent estimates of deforestation rates, or more generally land-use change, vary considerably, and debate continues over whether the rates of deforestation in the tropics are declining or increasing (FAO, 2001; Matthews et al., 2000). Only for specific, narrowly defined regions can one obtain reasonably reliable data on deforestation rates over specific time periods (e.g., Mertens and Lambin, 2000).

Establishing cause–effect relationships for deforestation or land use at various scales has also proven difficult even when the process appears well documented (Angelsen and Kaimowitz, 1999; Irwin and Geoghegan, 2001; Barbier, 2001). The standard explanation for deforestation in the tropics has been rapid population growth, associated poverty, and consequential environmental destruction (Leach and Mearns, 1988; Richards and Tucker, 1988; Mercier, 1991; Brown and Pearce, 1994; Sponsel et al., 1996). In selected areas, commercial exploitation and clear cutting are also important causes of deforestation (Torsten, 1992). However, conventional explanations for forest loss and environmental degradation have recently been questioned as too simplistic, general, or even misleading (Barbier, 2001). In the absence of a clear understanding of the role that various contributing explanatory variables may play in deforestation processes, let alone establishing cause effect relationships, it is not surprising that reforestation or forest conservation schemes have had relatively little or no success. Most of the reports on failures are buried in the gray or secondary literature (e.g., Bloom, 1998; IUFRO, 2001; Sharma et al., 1994; cf. Oates, 1999); relatively few are to be found in the primary literature (e.g., Olson, 1984; Elster, 2000); and rarely does one find reports of successful reforestation either via natural succession (e.g., Guariguata and Ostertag, 2001) or by human management practices (e.g., Lamb et al., 1997).

In this paper, we focus on deforestation processes and patterns of land use in the eastern wet tropical forests of Madagascar (Fig. 1). The prevailing perception is that the patterns and processes here are well understood. In fact the land-use change maps of Green and Sussman (1990) are commonly reproduced in textbooks as standard examples of deforestation processes. Nevertheless current and historical patterns of deforestation in Madagascar remain poorly understood, and controversial (e.g., Jarosz, 1993 versus Green and Sussman, 1990). Current estimates of forest cover in Madagascar vary by at least five-fold, from 42,000 km^2 for "closed forest," up to 158,000 km^2 for "natural forest," to 232,000 km^2 for "total forest and woodland," respectively, about 7, 27 and 40% of the land area of Madagascar (UNEP, 1998; UNEP-WCMC, 2001). This underscores the pervasive difficulty of estimating forest cover, which in part reflects differing definitions of forest (cf. Silander, 2000). In contrast, the forest cover in 1902 was estimated at about 20% of the land area (Pelet, 1902). In 1921, based on extensive field reconnaissance from 1900 to 1915, Perrier de la Bâthie estimated that about 19% (110,000 km^2) of Madagascar was in forest or woodland of one sort or another. But of this only about 35–70,000 km^2 (6–12%) was closed forest. In 1934, forest cover was estimated at only 10% of the land area (Grandidier, 1934). These figures conflict with estimates of forest cover in the 1960s: 33% forested in the early to mid 1960s (Humbert and Cours Darne, 1965) versus 21% a few years later (Le Bourdiec et al., 1969). The fact that these contemporary estimates of forest cover are so different is surprising, given the availability of aerial photography and more precise cartographic methodology. Satellite data from the 1970s onward have been able to provide only limited estimates of forest cover or deforestation rates. Virtually all of the available images of the wet tropical forests of the eastern Madagascar were too obscured by clouds through the 1990s to provide adequate estimates of forest cover, especially for the focal region of this study. In fact, the most recent available maps reproduce "current" forest cover for most of the east coast from the maps published in 1965 (Faramalala, 1995; Du Puy and Moat, 1999; see also Green and Sussman, 1990) with no new data. These sources thus indicate current forest cover for our focal region (Taomasina Province)