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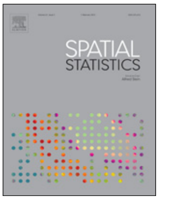

Use of spatial statistics to investigate early forest degradation activities as detected from satellite images

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ABSTRACT

Selective logging gives currently a major contribution to ongoing deforestation in the Brazilian Amazonia. The spatial distribution of log landing sites (LLS), i.e. the sites where logged trees are collected, serves as a proxy to the intensity of selective logging activities. In this study we analysed the LLS pattern in a study area that has a rapid deforestation. Actual LLS locations were extracted from a Landsat image of 2000 that covers a large part of the study area. We first used the inhomogeneous *J*-function. A kernel bandwidth of 20 km best modelled the non-stationarity, showing a strongly clustered LLS distribution. Second, the Area-interaction point process model incorporating information about distance of LLS to roads and to clear-cut deforested areas was applied. The model well explained the clustered LLS pattern and showed a significant effect of distance to roads. We concluded that this spatial statistical study helped to quantify and better understand the LLS pattern.
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1. Introduction

Landscape spatial patterns refer to the spatial heterogeneity in a landscape. Spatial heterogeneity means the composition, configuration and, in a broader sense, even the temporal aspects of the heterogeneity (Gustafson, 1998). Spatial patterns reflect processes which have been operating in the past

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and may be present in the future (Law et al., 2009). In a forest environment, spatial patterns may result from a number of different ecological processes, examples of which may include growth and mortality, interaction of silvicultural management, land use and climate (Comas and Mateu, 2007). As there is a strong link between patterns and processes (Gustafson, 1998), ecologists study spatial patterns to infer the existence of underlying ecological processes related to the phenomena under study (Watt, 1947). Knowledge of spatial patterns in a forest environment, therefore, may assist in management of forest resources.

In the Brazilian Amazonian forests, selective logging for timber is a major source of forest degradation (Uhl et al., 1991; Gerwing, 2002). Adverse effects of selective logging on the Amazonian forests include damages to forest phenology (Koltunov et al., 2009), increasing vulnerability of a forest to fire (Gerwing, 2002; Fearnside, 2005), forest fragmentation (Broadbent et al., 2008) and wide spread of deforestation (Uhl et al., 1991; Fearnside, 2005). An important challenge faced by forest researchers today is to detect and analyse the locations and patterns of forest perforations caused by selective logging for timber. Selective logging operations are almost impossible to monitor, as much of the Amazonian region is inaccessible. Remote sensing, due to its synoptic view and fast coverage, may serve as a viable source for the purpose. Log-landing sites (LLS), the locations where the collected timber is stored, can be detected from remote sensing images and may serve as a proxy for the selective logging activities in a surrounding area (Anwar and Stein, 2012).

There has been intensive work on analysing the deforestation patterns and processes in the Brazilian Amazonia and efforts have been made to model the deforestation processes using different spatial analytical tools (Apan and Peterson, 1998; Alvis et al., 1998). Spatially explicit analysis and modelling of the locations of forest degradation is, however, lacking. Due to small spatial extent of the LLS, it is natural to represent them as points in the maps derived from remote sensing images. A spatial point pattern analysis, then, may serve as an appropriate tool for analysing the process that determines the LLS distribution. On the other hand, as logging operations also vary in time (Matricardi et al., 2005); a spatial–temporal statistical analysis of the spatial distribution of selective logging is necessary to reveal its important temporal characteristics (Anwar and Stein, accepted for publication).

A spatial point pattern is usually a single realization of a spatial point process. The assumption of stationarity is often made to reduce the parameter space and to allow parameter estimation (Cressie, 1993) of a spatial point process. By stationarity it is understood that all properties of the spatial process are invariant under translation. We thus assume that the LLS density is constant across space. Real forest configurations, however, are seldom stationary. Inhomogeneity may arise as a result of the inherent spatial variability caused by environmental factors, or due to the interactions between the locations of the phenomenon under study or both. In spatial point process theory, the term 'interaction' refers to the probability of points of the same or different types occurring in close proximity (Illian and Burslem, 2007). In a forest structure, different factors such as environmental heterogeneity and geographical configurations (e.g. mountain slope) can cause inhomogeneity (Comas et al., 2009). For a LLS pattern, the stationarity assumption could be violated if there are large areas of low or zero density of LLS over the region under study.

Dealing with inhomogeneity has been a focus of spatial statistical research (Law et al., 2009). The efforts have been directed towards finding appropriate tools for the analysis and formulating suitable models to address nonstationarity of the point processes. Baddeley et al. (2000) developed an inhomogeneous version of Ripley's K-function (Ripley, 1977) as an important contribution for investigating the intensity structures and analysing the spatial distribution of point patterns. Another summary measure, the inhomogeneous J-function (J_{inhom}) was proposed by Van Lieshout (2011). The J_{inhom} is receiving popularity because, unlike the inhomogeneous K-function, its definition does not depend upon the choice of origin and hence is computationally convenient. A tricky issue involved in calculation of inhomogeneous summary functions is the choice of kernel bandwidth (Law et al., 2009), since there is no rigorous mathematical theory available for its optimal choice (Illian et al., 2008).

Modelling of a nonstationary process is done using Monte Carlo Markov Chain (MCMC) methods. In the presence of interaction among LLS, such methods may become computationally extensive as they need to incorporate interaction terms as well as the spatially varying LLS density (Baddeley et al., 2000). The LLS data are commonly found to be of an inhomogeneous structure and a number of different ecological and geographic factors may influence their distribution pattern. A model can be

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