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Assessing sustainability indicators for tropical forests: Spatio-temporal heterogeneity, logging intensity, and dung beetle communities

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Abstract

Sustainable management of tropical forests has been identified as one of the main objectives for conservation of global biodiversity and management of carbon stocks. To achieve this goal, managers need tools to assess the sustainability of current management practices. Several international initiatives have undertaken the development of sets of criteria and indicators to help managers move towards sustainability. Among the indicators considered, the structure and composition of dung beetle communities have been identified as excellent indicators of ecological sustainability. However, as occurs with most indicators of the ecological sustainability of forest management, dung beetle surveys require intensive field work making their application over large areas expensive, time consuming, and logistically challenging. A need for prioritization is evident. This work presents a novel approach to the assessment of the Center for International Forestry Research (CIFOR) ecological sustainability indicator I.2.1.2: "The change in diversity of habitats as a result of human interventions is maintained within critical limits as defined by natural variation and/or regional conservation objectives". Using variography of vegetation index data derived from remotely sensed imagery, we show (1) how the differences in forest structural heterogeneity observed between forest management units and natural areas can be used to identify priority areas for field survey of ecological sustainability indicators (hereafter "priority-for-survey") and (2) how these priorities correspond to dung beetle community structure and composition. Links between temporal change in forest structural heterogeneity, logging intensity, and dung beetle community structure and composition were established by means of correlation analysis and matrix regression modeling. We found that areas ranked as low priority-for-survey based on image analysis showed no significant difference in dung beetle species richness or diversity from natural reference areas. Further, we found significantly higher dung beetle species richness and diversity estimates in areas ranked as moderate or moderate-low priority-for-survey over the low and reference areas. Finally, the dung beetle community composition in the high priority-for-survey category was significantly less rich and less diverse than any other category. We identified a logging intensity threshold of four trees per hectare as a transition to significant differences in forest structural heterogeneity and the richness and diversity of associated dung beetle communities.

Keywords: Sustainable management; Criteria and indicators; Tropical forests; Structural heterogeneity; Dung beetles; Costa rica

1. Introduction

Sustainable management of tropical forests has been identified as a main objective for global conservation of biodiversity and carbon stocks as they are among the most diverse and endangered biomes (CIFOR, 2000; FAO, 2005; Vieira et al., 2004). Any forest not considered economically productive or protected by a conservation status is at risk of conversion into other types of land use. However, not all forest management schemes are sustainable and managers lack tools to evaluate the sustainability of their practices. Acknowledging this deficiency, several initiatives have undertaken the development of sets of criteria (a standard that a management is judged by (CIFOR, 2000)) and indicators (any variable or component of the forest ecosystem or management system used to infer the status of a particular criterion (CIFOR, 2000)) (C&I processes) that managers can use as tools in the evaluation of the sustainability of their specific operations (CIFOR, 2000; Ghazoul and Hellier, 2000; Franc et al., 2001; McGinley and Finegan, 2003; Finegan et al., 2004). The majority of the indicators proposed are based on

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scientific research for conservation of biological diversity in managed forest systems (Stork et al., 1997; CIFOR, 2000). In most cases, the question of how to apply and assess these C&I sets remains to be answered from an operational, field-based perspective (Ghazoul and Hellier, 2000; Franc et al., 2001; McGinley and Finegan, 2003; Finegan et al., 2004).

Dung beetles are commonly proposed as indicators of biodiversity due to their close relationship with all types of vertebrate fauna dung and their role as decomposers (Halffter and Favila, 1993; Hill, 1996; Favila and Halffter, 1997; Aguilar-Amuchastegui, 1999; Aguilar-Amuchastegui et al., 2000; Davis et al., 2001; Halffter and Arellano, 2002; Pineda et al., 2005; Scheffler, 2005; Andresen, 2005). They have proven to be an effective indicator group that can be used by forest managers and workers to survey ecological sustainability indicators and for forest management certification surveys (Finegan et al., 2004). However, as with most forest management ecological sustainability indicators, dung beetles need to be surveyed in the field (Aguilar-Amuchastegui et al., 1999; Ghazoul, 2001; Finegan et al., 2004). These surveys are limited in extent and time consuming (Lambin, 1999; Farthing et al., 2001; Fahrig, 2003; Foody and Cutler, 2003). As the number of forest areas to be surveyed or the total area under management increases, the personnel and time required also increases and surveying becomes impractical: there is clear need for an approach to the prioritization of areas to be surveyed in the field.

Tropical forests are not static ecosystems; they manifest dynamic structural heterogeneity that results from specific natural histories of episodes of disturbance and recovery. These disturbance regimes typically create mosaics of regeneration stages (early, intermediate, advanced, and mature forest) that differ in microclimate, vegetation structure, and faunal composition, including dung beetle species community structure and composition (Morgan et al., 1994; Finegan, 1996; Delgado et al., 1997; Ghazoul and Hellier, 2000; Finegan and Delgado, 2000; Davis et al., 2001; Weishampel et al., 2001; Andresen, 2005). The horizontal distribution of regeneration stages provides a forest with its structural heterogeneity (Finegan, 1996).

Forest management can change forest structural heterogeneity depending on its harvest intensity (viz., the number of trees, basal area, or cubic meters of wood removed per ha) (Delgado et al., 1997; Ghazoul, 2001; Ghazoul and Hellier, 2000; CIFOR, 2000; Finegan et al., 2004). Accordingly, CIFOR (2000) established as one of its ecological sustainability indicators: ‘‘Changes in diversity of habitats as a result of human interventions are maintained within critical limits as defined by natural variation and/or regional conservation objectives’’ (I.2.1.2.). Thus, if a given management scheme maintains the relative abundance and distribution of the successional stages that provide forests with a diversity of habitats and structural heterogeneity within the limits framed by natural regimes, it may be considered sustainable. On the other hand, any scheme that fails to do so after a reasonable recovery time would be considered unsustainable.

Traditionally, forest structural heterogeneity is surveyed in the field identifying the regeneration stage of sample plots along forest inventory lines (Finegan et al., 2004). However, it can also be assessed by remote sensing (Lambin, 1999; Couteron et al., 2005; Foody and Cutler, 2003; Lim et al., 2003; Kalacska et al., 2004; Lu et al., 2004; Wulder et al., 2004; Ingram et al., 2005). Structural aspects such as canopy architecture (Danson, 1995), understory leaf litter (Franklin et al., 2002), biomass, age, density, mean tree height, and basal area (Lee and Nakane, 1996; Lu et al., 2004) have been measured using passive sensors such as Landsat TM and ETM + (Asner et al., 2002, 2004; Lu et al., 2004; Feeley et al., 2005; De Wasseige and Defourny, 2004; Souza et al., 2005) and SPOT (Feeley et al., 2005; De Wasseige and Defourny, 2002, 2004). Active sensors such as LiDAR (Lefsky et al., 2002; Lim et al., 2003; Santos et al., 2003) and Synthetic Aperture Radar (Israelsson and Askne, 1995; Pulliainen et al., 2003) have proven useful for the characterization and monitoring of forest structure. The use of remote sensors in evaluating forest stand characteristics (Wulder, 1998; Lim et al., 2003; Lu et al., 2004), suggests that they may also be useful for evaluating CIFOR’s indicator I.2.I.I.

There are several methods for analyzing remotely sensed imagery to assess the biophysical characteristics of vegetation structure (Ingram et al., 2005). One common approach combines the reflectance measured at various spectral bands (blue, green, red, and near infra-red light) into a vegetation index (VI). Biophysical variables related to forest structure, e.g., successional and phenological stage, chlorophyll content, net primary productivity (NPP), leaf area index (LAI), and the fraction of absorbed photosynthetically active radiation (FPAR), have been shown to be related with VIs, such as the Normalized Difference Vegetation Index (NDVI; Tucker, 1979; Baret and Guyot, 1991; Huemmrich and Goward, 1997; Birky, 2001) and the recently developed Wide Dynamic Range Vegetation Index (WDRVI) (Gitelson, 2004; Viña et al., 2004; Viña and Gitelson, 2005).

Among the methods for quantifying spatial heterogeneity, geostatistical tools such as correlograms and variograms have been used in ecological studies (Isaaks and Srivastava, 1989; Légendre and Fortin, 1989; Riera et al., 1998; He et al., 1996; Pastor et al., 1998; Goodin et al., 2004; Colombo et al., 2004). An advantage of variography is an explicit quantification of two aspects of spatial heterogeneity: the amount of spatial variation (or total sill) and the average distance (or range) within which observations are significantly correlated (Henebry, 1993; He et al., 1996; Goodin and Henebry, 1997; Goodin et al., 2004; Colombo et al., 2004). This latter measure can be considered some approximation to the average patch size exhibited by the data. (Its strict interpretation, however, is fraught with caveats.)

The present study sought to establish the relationships between (1) change in forest structural heterogeneity, (2) dung beetle community structure and composition, and (3) a key forest management variable: logging intensity. The rationale is that once the relationships between these three aspects have been characterized, remote sensing of forest structure can serve as an important practical tool for guiding sustainable management of tropical forests and conserving vulnerable carbon stocks. Our main hypothesis is that managed forest areas that [do not] exhibit significant differences in forest structural