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Towards rapid assessments of tree species diversity and structure in fragmented tropical forests: A review of perspectives offered by remotely-sensed and field-based data

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A B S T R A C T

With forest fragmentation continuing in many parts of the tropics, it is likely that fragmented forests will become the rule for most remaining global tropical forests in the next decades. In this context, there is a need for practical tools to assess and monitor fragmented forests if we are to conserve tree species diversity as much as possible. Several methods, either using (1) field-based or (2) remote-sensing approaches could be used to achieve this goal. This paper aims at providing a state-of-the-art review of both approaches in order to make recommendations for rapid and cost-effective assessments of tree species diversity and forest structure, with specific applications in studies of fragmented tropical forests. Overall both methods have pros and cons, depending on the type of data needed to address the research objectives and the quantity of resources available. We suggest combining the use of both field-based and remotely-sensed methods as they can be complementary. Remote-sensing data should be used to predict and map the tree species diversity and stand structure at regional scales, while field-inventories provide accurate information at local scales and allow validation of remotely-sensed data. For field-inventories, we recommend the use of small (e.g. 20 × 50 m) plots with a 10 cm DBH minimum measurement. In terms of remotely-sensed techniques, if funding is sufficient, airborne imagery seems the best regarding the quality of information (i.e. hyperspectral and hyperspatial imagery, LiDAR). If funding is limited, a cost-effective alternative providing reasonably accurate estimates would be the use of high-resolution satellite imagery such as Worldview. Ultimately, for studies where data accessible for free is the only possible option, we recommend the use of Sentinel-2, although it is relatively coarser in terms of quality. However, further research needs to be done to validate these approaches in fragmented tropical forests.

1. Introduction

Tropical rainforests are recognized for hosting a significant proportion of global biodiversity (Gaston, 2000; Myers et al., 2000) and their conservation constitutes a major challenge (Koh and Sodhi, 2010). Over the last five decades, increases in logging, agriculture and urban growth have led to significant losses of tropical forest (Houghton, 1994; Lewis et al., 2015; Rosa et al., 2016) resulting in unprecedented fragmentation of this habitat (Laurance and Bierregaard, 1997; Groombridge and Jenkins, 2000; Koh and Wilcove, 2008; Peres et al., 2010). A recent study revealed that 70% of remaining global forests are within 1 km of the forest's edge, subject to the degrading effects of fragmentation (Haddad et al., 2015). Global patterns of tropical forest fragmentation predict large increases in the total number of forest remnants in the future (by a factor of up to 33 over the next 50 years), as well as a decrease in their size (Taubert et al., 2018). With fragmentation continuing in many parts of the tropics, fragmentation might become the rule for most of the remaining global tropical forests in the next decades. Alroy (2017) reported that habitat disturbances have already led to a loss of about 30% of tree species in tropical forests. In this context, tropical forests urgently need to be monitored and closely managed if we are to conserve tree species diversity as much as possible.

Besides the direct loss of diversity caused by habitat reduction, fragmentation affects tree communities through impacts of edge-effects on the remaining fragments and increases in isolation which limits connections between them (see Fahrig, 2003; Harper et al., 2005; Ewers and Didham, 2006; Laurance, 2008; Heinken and Weber, 2013). In addition, because forest remnants are more accessible than continuous forests, after fragmentation, they are often exposed to human-induced

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disturbances such as illegal timber harvesting and land-clearance by small-scale farmers (Hamer et al., 1997; Fahrig, 2003). Finally, due to their long lifespans, tree species are affected by fragmentation through slow long-term processes that lead to time-delayed species extinctions (Helm et al., 2006; Vellend et al., 2006; Metzger et al., 2009; Krauss et al., 2010); a process known as "extinction debt" (Tilman et al., 1994). All these factors combined together make it very difficult to estimate the real impact of fragmentation on tree communities over long time periods.

As noted by Kangas and Maltamo (2006), "All decision-making requires information. In forestry, this information is acquired by means of forest inventories, systems for measuring the extent, quantity and condition of forests." In this context, forest managers, as well as policy makers, have a need for practical forest inventory tools to assess and to monitor trends for biodiversity in fragmented tropical forests, thus providing information in support of management or intervention plans. While criteria and indicators for fragmented tropical forests may vary according to policy objectives (e.g. sustainable timber harvesting, carbon sequestration, maintenance of biodiversity at an ecosystem or landscape level, conservation of rare, endangered or valuable species), all are underpinned by information gained from forest inventories.

Although substantial efforts have been made by researchers over the last decades, the composition and structure of large areas of tropical forests remain poorly studied (Foster et al., 1998; Feeley and Silman, 2011), thereby making forest management decisions difficult in many countries. This is even more relevant in fragmented tropical forests, considering that while most ecological studies have focused on undisturbed tropical forests, research has also highlighted possible conservation values of disturbed or fragmented tropical forests (e.g. Turner and Corlett, 1996; Baynes et al., 2016). In classical field-based methods, much of the time and resources necessary to inventory sites are used for travel, which makes time spent in the field extremely valuable (Baraloto et al., 2012). Thus, a rapid inventory method providing information on both biodiversity (i.e. number of species) and forest structure would represent a major tool to improve our ability to plan for management and conservation of fragmented forests. Along with several methods using field-based approaches, the last decades have also seen increasing development of technologies using remote-sensing that could be used to achieve this goal.

Many studies have been published regarding rapid assessment of tree species diversity and forest structure based on field inventories (e.g. Higgins and Ruokolainen, 2004; Jayakumar et al., 2011; Baraloto et al., 2012; Arellano et al., 2016). Although several studies and reviews also exist about the potential of remote-sensing for forest inventories (e.g. Nagendra, 2001; Chambers et al., 2007; Gillespie et al., 2008; Fassnacht et al., 2016; Lausch et al., 2016), only a few have addressed an overview of these technologies for assessments of both taxonomic and structural diversity at the same time (Lausch et al., 2016; Mulatu et al., 2017). In addition, to our knowledge very few studies have properly reviewed and compared the possibilities offered by field-based and remotely-sensed approaches at the same time (e.g. Bustamante et al., 2016). Even though this was attempted by Jayakumar et al. (2011), when this review was published they concluded that remote-sensing technologies needed more development and research. More importantly, while these studies were focused on undisturbed forests, to our knowledge no study has addressed what is best suited to highly-disturbed fragmented forests. In that context, this paper aims at providing a state-of-the-art review of both field-based and remotely-sensed approaches in order to make recommendations for rapid and cost-effective assessments of tree species diversity and forest structure, with specific applications in studies of fragmented tropical forests.

Studies in fragmented tropical forests have several requirements. Forest fragmentation has usually been described as a non-random process and the configuration and shape of remaining fragments are often influenced by environmental factors such as soil type, topography or wetness (Turner, 1989; Laurance, 2008; Ibanez et al., 2017). Therefore, most forest remnants present a high variability of sizes and shapes, especially over regional scales (Ranta et al., 1998; Hill and Curran, 2003; Ibanez et al., 2017), which is a problem for both field-based and remotely-sensed techniques. In contrast, most studies in contiguous tropical forests do not have to deal with this type of problem and, for example, allow implementation of very large survey plots of up to 50 ha (e.g. Lee et al., 2002). Recently, Taubert et al. (2018) reported that varying patterns of local deforestation (assessed from global data on forest cover) produced intriguingly similar patterns of tropical forest fragmentation at the continental scale. In this study, mean (median) sizes of global tropical forest fragments were 17, 13 and 13 ha for the Americas, Africa and Asia-Australia respectively, and are expected to decrease in future (Taubert et al., 2018). Forest fragments also presented very similar fractal dimension and perimeter scaling in the three continents. In their study at a landscape scale, even smaller fragment sizes were reported by Ibanez et al. (2017). Forest fragments presented irregular shapes and had sizes ranging from 0.1 to 54.6 ha with a median size of only 1.6 ha. Assessment techniques should thus also be able to deal with such small sizes of forest fragments.

Finally, another important requirement is the geographic area covered by an assessment. Although the geographic area of a study usually depends on both research objectives and resource availability, fragmented landscapes could theoretically be studied on scales from a few thousand hectares (e.g. Baynes et al., 2016; Ibanez et al., 2017) up to the total of tropical forest areas at the continental scale (940, 577 and 391 Mha for Americas, Africa and Asia-Australia respectively (Taubert et al., 2018)). Assessment methods addressing the future of fragmented tropical forests should thus deal with wide ranges in the assessment scale, and in the shape and size of fragments, while also being affordable. This is particularly important since most of this topic concerns developing countries where limited funding may only allow studies on a restricted scale.

2. Field-based inventory methods

Over the last decades, studies of tree species diversity in tropical forests have been increasingly standardized in order to allow comparison among research groups (Condit, 1995; Condit et al., 2002; Malhi et al., 2002; Arellano et al., 2016). Some of the field-based inventory methods commonly used have been summarized in Table 1.

Overall, all field-based inventory methods have pros and cons and the most appropriate largely depends on (1) the quantity of resources available and (2) the type of data needed to address the research objectives. However, for specific applications in fragmented forests studies, several important aspects need to be considered. Firstly, an important decision is whether the plots need to be permanent or not. Permanent plots have considerable advantages for studies of forest dynamics and tree-species demographic rates. However, because individual trees need to be tagged and spatially located within permanently marked plots, they require a significant amount of time and effort to establish and monitor (Arellano et al., 2016). Temporary plots, on the other hand, do not require tagging and mapping of individual trees or permanent plot delineations, and each individual tree is only measured once. Since the objective in fragmented forests studies is to gather basic information on forest structure and composition over large areas, time- and cost-effective temporary plots are likely to be more suitable.

Considering the variety of methods found in the literature, including circular/square/rectangular plots or transects (see Table 1), other important aspects are both the size and the shape of the plots. Initially recommended by the Food and Agriculture Organization (FAO, 1981), one of the most widespread field-based forest inventory methods is the 1-ha square plot (e.g. Phillips et al., 2009; Stropp et al., 2009). However, because of aggregative patterns and rare species in tropical forests, recent studies have suggested this approach is not the most appropriate to measure species diversity (Phillips et al., 2003b). This