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Research paper

Forest restoration assessment in Brazilian Amazonia: A new clustering-based methodology considering the reference ecosystem

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ABSTRACT

Techniques for forest restoration have been widely developed over the past decades, allowing the reestablishment of vegetation in extreme cases such as surface mining. However, there are still issues related to management and monitoring that require further understanding, especially concerning comparisons with reference ecosystems. In this study, hierarchical agglomerative clustering (HAC) with uncertainty estimation is proposed as a methodology for forest restoration assessment. For this purpose, analysis was made of phytosociological variables for 27 plots located in reforested closed mines and in the Amazon forest reference ecosystem. The technique grouped the reference ecosystem separately from the reclamation sites. The HAC was affected by dependency among the analyzed variables, and heterogeneity was observed for all the phytosociological parameters in the cluster groups formed by the mining locations. However, each group showed specific characteristics related to the different environmental conditions and the forest restoration performance. The results demonstrated that HAC with uncertainty estimation was more suitable for defining groups, compared to the classical approach, offering a promising methodology for evaluation of the outcomes of forest restoration and for guiding management actions in disturbed tropical forests.

1. Introduction

Mining activities are responsible for almost 4% of the gross domestic product of Brazil, corresponding to U$ 85 billion in 2013, with a U$ 27.4 billion budget surplus attributed to this activity alone (ICMM, 2013). However, despite all the economic and social benefits associated with this sector, the exploitation of mineral reserves in important ecosystems, such as the Amazon Forest, requires careful management in order to avoid negative environmental impacts and associated problems (Phillips, 2016; Souza et al., 2011; Monteiro, 2005; Pedlowski et al., 1997; Smith et al., 1991).

In surface mining, especially, there are the creation of huge overburden dumps and voids, which mostly consist of large boulders and loose rock fragments, devoid of organic matter and nutrients (Mukhopadhyay et al., 2014). In these situations, considerable restoration effort is required to reestablish the preexisting multi-scale ecosystem processes, or a condition close to them (Parrotta and Knowles, 2001).

Even with prior planning, the different levels of landscape modification, together with different forms of exploitation, the reclamation methods adopted, and availability of financial resources, are determining factors of the new environment formed, which can differ from the characteristics of the original ecosystem (Stanturf et al., 2014; Li et al., 2006; Parrotta and Knowles, 2001; Miao and Marrs, 2000; Bradshaw, 2000, 1997; Bradshaw, 1984).

Since these ecosystems present high levels of complexity, both qualitative and quantitative, the evaluation of restored environments and the outcomes of land reclamation remains a very difficult task, especially in terms of understanding how to measure it and how to know when the reclamation ends (Leinfelder et al., 2015). Considering forest restoration, comparison with reference ecosystems has been highlighted as a crucial aspect, since it can provide criteria to evaluate the outcomes of actions performed and identify existing technical limitations that may not allow a full restoration (Rosenfield and Müller, 2017; Lei et al., 2016; Ribeiro et al., 2016).

There has been a great effort in the scientific community to debate

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forest restoration concepts (Lima et al., 2016; Balaguer et al., 2014) and techniques (Ribeiro et al., 2015; Stanturf et al., 2014; Rodrigues et al., 2009), in some cases with narrow scopes only valid for local conditions (Young et al., 2003). Future challenges involving ecological restoration will require measurement and monitoring methods that are more comprehensive, enabling evaluation of whether the ecosystem function is developing towards the desired state (Halme et al., 2013).

The aim of the present work was to explore this topic, with proposal of a clustering-based methodology for forest restoration assessment. A case study was employed to test the technique, evaluating the phytosociological variables and soil characteristics of forest restoration projects at seven deactivated mines in Brazilian Amazonia. Hierarchical agglomerative clustering (HAC) was employed because it is one of the simplest clustering methods, is generally applicable to most types of data, does not require extensive prior knowledge, and enables results to be easily visualized graphically in the form of dendrograms (Legendre and Legendre, 2012; Romesburg, 2004; Jongman et al., 1995). The methodology included a robust routine constructed using the R software Pvclust (Suzuki and Shimodaira, 2015, 2006), with estimation of uncertainty in the cluster analyses in order to improve evaluation of the results.

This work was based on the hypothesis that HAC with uncertainty estimation could be a useful tool to evaluate tropical forest restoration, allowing the identification of driving forces, technical limitations in restoring complex forests, and management elements.

2. Materials and methods

2.1. Study location

Jamari National Forest is located in the municipality of Itapuã do Oeste, in Rondônia State, Brazil (latitude 09° 00′ 00″ S, 09° 30′ 00″ S; longitude 62° 44′ 05″ W, 63° 16′ 54″ W) (Fig. 1). The total area is 215,000 ha, of which 90% is covered by open tropical rainforest (Amazon biome) and 10% consists of mining areas, with one operating mine and seven other deactivated in the process of reclamation.

The climate is tropical rainy (Aw, according to the Köppen scale), with a well-defined dry season in winter, from July to August, and a rainy season in summer, from December to March (Ribeiro et al., 2016). The main soils are dystrophic Red-Yellow Latosol (Kandiudult) and dystrophic Red-Yellow Podzolic (Paleudult), covered by open rainforest with small patches of tropical rainforest, characterized by a high richness of spaced arboreal individuals and a diverse wildlife, including several species threatened with extinction (MMA/IBAMA, 2005; Soil Survey Staff, 1999).

2.2. Treatments description

The study was undertaken at seven deactivated mines, previously used for cassiterite extraction, which have been under reclamation since the 1990s, aiming at reestablishment of the dominant Amazonia landscape. Due to the heterogeneity of the mined soil, an environmental zoning of the post-mining locations was performed before site preparation and initiation of activities, employing a preliminary environmental damage assessment (Ribeiro et al., 2015). All the soil substrates of the deactivated mines were previously classified into three main environmental zones, according to their physical and chemical characteristics:

[1] Pit mine: Soil substrate obtained due to earthworks in surface soil, following exposure of the slopes, construction of berms, construction of access roads, and other operations requiring the excavation, removal, or landfill of surface soil. This substrate maintained the characteristics closest to those of the original soil.

[2] Tailings (dry and wet): Remnant substrate composed of a heterogeneous mass of material derived from the filling of ore removal locations. These areas were filled with sediment of variable grain size and were drained or partially drained, subject to flooding, and devoid of organic matter. The characteristics of this substrate depended on the physical and geochemical properties of the rock from which it derived, but it was usually nutrient-poor and supported little plant growth. The dry tailings were located near the containment dam, having large particle size (mainly sand), little or no soil structure, low or very low natural fertility, excessive drainage capacity, and low water retention capacity. The wet tailings were away from the dam containment, usually near watercourses, with a tendency for fine particle sizes and a predominance of clay. Due to their proximity to watercourses, these tailings could remain flooded for part of the year.

[3] Capped tailings: Substrates formed by the covering of tailings with topsoil. The topsoil was usually obtained from other locations where mines were in the process of being opened, and therefore contained organic matter and seeds, favoring the reestablishment of vegetation. As tailings are highly erodible, with adverse effects on plant growth and in water courses, this procedure has become a requirement in recent Brazilian environmental laws. As a result, this substrate tended to have better physical and chemical characteristics, compared to the dry and wet tailings, although such characteristics were nonetheless highly dependent on the properties of the deposited material.

Following the environmental damage assessment, actions that were implemented prior to revegetation with native species included topographic reconstruction, control of runoff, and soil restoration, using composting associated with green manuring, chemical fertilizers, and liming, depending on the characteristics and extent of the environmental damage at each site (Ribeiro et al., 2015; Yada et al., 2015; Longo et al., 2011).

2.3. Floristic structure and composition

A total of 91 planted species, belonging to 37 families, were used in the forest restoration of the overburdens. Of all species, 22 were exclusively of natural regeneration, representing 29% of the total sampled individuals. The botanical families with the greatest numbers of individuals were Fabaceae, Myrtaceae, and Clusiaceae, with the first two also showing the highest number of species. Members of families that were not planted, including Cecropiaceae, Clusiaceae, Cannabaceae, Malvaceae, Melastomataceae, Moraceae, Piperaceae, and Siparunaceae, were found in the mined areas as well as in the natural forest. The most common species were *Inga laurin* and *Syzygium cumini*, both with high density, due to their extensive use in the revegetation process, while among the naturally regenerated individuals, the most common species were *Bellucia grossularioides*, *Astrocarium aculeatum*, and *Trema micrantha*.

2.4. Data collection

The study was performed using 19 plots (each measuring 50 × 50 m) located in the north-south direction from the access roads. The data were collected in 2010, in areas with different planting ages ranging from 3 to 9 years (Table 1). In addition, 8 plots in the surrounding areas, in closed canopy forest (undisturbed Amazon forest) and open canopy forest (disturbed Amazon forest), were adopted as reference ecosystems and were used to assess the performance of the forest restoration, with data also collected in 2010.

The average height was measured for trees with diameter at breast height (DBH) greater than 10 cm. Basal area (Eq. (1)), average species richness, and number of naturally regenerating individuals were obtained by counting trees with DBH smaller than 10 cm. The average species richness was obtained by calculating the total species sampled in 50 × 50 m plots, and the number of naturally regenerating individuals was obtained by counting the number of naturally occurring tree seedlings with height smaller than 3 cm in 10 × 10 m plots, positioned inside the 50 × 50 m plots. The same variables were measured in secondary (open canopy) and mature (closed canopy) forests in the