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Assessing the structural differences between tropical forest types using Terrestrial Laser Scanning

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ABSTRACT

Increasing anthropogenic pressure leads to loss of habitat through deforestation and degradation in tropical forests. While deforestation can be monitored relatively easily, forest management practices are often subtle processes, that are difficult to capture with for example satellite monitoring. Conventional measurements are well established and can be useful for management decisions, but it is believed that Terrestrial Laser Scanning (TLS) has a role in quantitative monitoring and continuous improvement of methods. In this study we used a combination of TLS and conventional forest inventory measures to estimate forest structural parameters in four different forest types in a tropical montane cloud forest in Kafa, Ethiopia. Here, the four forest types (intact forest, coffee forest, silvopasture, and plantations) are a result of specific management practices (e.g. clearance of understory in coffee forest), and not different forest communities or tree types. Both conventional and TLS derived parameters confirmed our assumptions that intact forest had the highest biomass, silvopasture had the largest canopy gaps, and plantations had the lowest canopy openness. Contrary to our expectations, coffee forest had higher canopy openness and similar biomass as silvopasture, indicating a significant loss of forest structure. The 3D vegetation structure (PAVD – Plant area vegetation density) was different between the forest types with the highest PAVD in intact forest and plantation canopy. Silvopasture was characterised by a low canopy but high understorey PAVD, indicating regeneration of the vegetation and infrequent fuelwood collection and/or non-intensive grazing. Coffee forest canopy had low PAVD, indicating that many trees had been removed, despite coffee needing canopy shade. These findings may advocate for more tangible criteria such as canopy openness thresholds in sustainable coffee certification schemes. TLS as tool for monitoring forest structure in plots with different forest types shows potential as it can capture the 3D position of the vegetation volume and open spaces at all heights in the forest. To quantify changes in different forest types, consistent monitoring of 3D structure is needed and here TLS is an add-on or an alternative to conventional forest structure monitoring. However, for the tropics, TLS-based automated segmentation of trees to derive DBH and biomass is not widely operational yet, nor is species richness determination in forest monitoring. Integration of data sources is needed to fully understand forest structural diversity and implications of forest management practices on different forest types.

1. Introduction

Tropical forests typically have high diversity, as they are characterized by a more complex canopy structure when compared to other forest types (Ghazoul and Sheil, 2010; Whitmore, 1982). Structurally complex habitats provide a large number of niches for different animal and plant species (habitat heterogeneity hypothesis; Tews et al., 2004). Increasing anthropogenic pressure leads to habitat loss, from

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deforestation that reduces the total forest area into smaller, isolated forest patches (Zipkin et al., 2009). In addition, degradation of remaining forests through selective logging, unsustainable use and extensive hunting leads to habitat loss (Harrison, 2011; Ticktin, 2004). In many seemingly intact forests the understorey has been heavily affected by human use, through cutting of poles for construction or fire wood, or planting of understorey species that are important commodities, such as coffee and cocoa (Harrison, 2011). Both processes lead to a steep decline in flora and fauna diversity with increasing degradation (Barlow et al., 2016; Pettorelli et al., 2014) and can for instance lead to 'empty forests' with no large animals remaining under an intact forest canopy (Redford, 1992). Accurate characterization and measurement of the intensity of forest management and use is required to understand the drivers of forest degradation, to prevent further degradation and to plan restoration actions (Ghazoul et al., 2015; Ghazoul and Chazdon, 2017). Anthropogenic pressure not only affects forest biodiversity, but also the provision of other ecosystem functions, such as carbon storage (Kissinger et al., 2012), soil stabilization, and water provision (Ellison et al., 2017). Besides the type, also the intensity and frequency of the disturbance events, and the time elapsed since the last event is important (Barlow et al., 2012). The combined effects of different management practices and the way they affect forest structure is not always clear, hampering the identification of management priorities for avoiding further forest loss and for restoring degraded forests (Berenguer et al., 2014).

To what extent, and in what way, forest structure is affected through forest degradation likely depends on the type of forest management. In this study, we assess the difference in forest structure between four forest types, characterized by different forest management practices, in the montane cloud forest of the UNESCO Kafa Biosphere Reserve, southwest Ethiopia. This area is a biodiversity hotspot and is considered the origin of the Arabica coffee (*Coffea arabica*). However, in the last decades large areas of these unique forests have been converted to other land-uses (Tadesse et al., 2014). Many of the previously untouched intact forests are currently managed, for example as semi-forest coffee systems, or as forests used for fuelwood collection and/or grazing by cattle (i.e. silvopasture). Other types of management in the area include the total clearance of natural forest for plantations for wood production and agriculture. In intact forest, the vegetation is dense in both understory vegetation (i.e. < 10 m) and in the canopy, with little light reaching the understory vegetation. Management in the coffee forests often imply the removal of most understory vegetation, while still leaving most of the canopy intact to provide shade for the coffee plants (Schmitt et al., 2009). *Coffea arabica* grows up to 10 m high, but is often pruned for easier harvesting and is planted with enough spacing, leaving a less dense vegetation structure. Management in the silvopasture system are diverse and can include fuelwood collection, grazing by cattle, and forests can be left to regrow after earlier use, which can result in a heterogeneous forest structure. Overall, silvopasture areas have a more open understory and canopy, and large canopy gaps. For plantations we assume a homogeneous canopy, with no canopy gaps and very little light reaching the ground floor, limiting the development of understory vegetation.

Generally, 3D (three dimensional) structural changes in forests are monitored in permanent sample plots in which trees are measured for their stem diameter and height, are mapped, and species are identified. Such conventional forest inventory methods capture some of the horizontal and vertical forest structural parameters, like aboveground biomass (Day et al., 2014), frequency distributions of canopy height (Brockelman, 1998), occupation of vegetation in space within canopy gaps (Bongers, 2001; van der Meer, 1997), and canopy openness (Chazdon and Pearcy, 1991; Oliver and Larson, 1996). However, to characterize the full spatial heterogeneity in forest structure, detailed 3D imagery is needed to measure an array of structural parameters, including the location of vegetation volumes (and in absence of this, empty-ness) in 3D space. These parameters are important for guiding management priorities or monitoring sustainable practices. Terrestrial Laser Scanning (TLS) provides high-accuracy data on both vertical and horizontal forest canopy structure (Liang et al., 2016; Palace et al., 2016; Wilkes et al., 2017) and therefore is promising for detailed monitoring of forest structure. It is well established that conventional measurements can be useful for management decisions, but it is believed that TLS has a role in quantitative monitoring and continuous improvement of methods. TLS provides a rapid, full coverage of the surrounding area and produces a high-detail 3D point cloud, which allows the estimation of a range of parameters such as canopy height (Palace et al., 2015), number of layers (Palace et al., 2016), Plant Area Volume Density (PAVD) (Calders et al., 2015b) and tree volume (Calders et al., 2015a; Ferraz et al., 2016). PAVD indicates the plant surface area to volume ratio, and provides a consistent, detailed quantification of vegetation elements (e.g. leaves, branches and stems) in a certain space. Consistent monitoring of changes in 3D structure is needed to monitor forest management implications, and here TLS could be an add-on or an alternative for monitoring conventional forest structure parameters. TLS-derived PAVD has been used to assess forest phenology (Calders et al., 2015b) and structural differences among forest types (Ashcroft et al., 2014), but effects of forest degradation have not been assessed. Small changes are difficult to detect by conventional satellite sensors due to their limited canopy penetration (Lefsky et al., 2002). Although synthetic aperture radar (SAR) and airborne laser scanning (ALS) have been successfully used to measure the 3D forest structure (Disney et al., 2006; Mura et al., 2015) and disturbances in the canopy (Joshi et al., 2015a), the data are still limited to the birds-eye view of the canopy. TLS fills this gap by measuring both forest understorey vegetation and the canopy.

In this study we assess the forest structure in the Kafa region in Ethiopia of plots under four management types: (i) untouched natural forest (intact forest) with no signs of management, (ii) coffee forest, (iii) silvopasture and (iv) plantation. We compare 3D forest structure between these types based on conventional forest inventory methods and on TLS. We hypothesize that (1) aboveground biomass (AGB), tree density, basal area (BA), and diameter at breast height (DBH) are highest in intact forest and plantation, and slightly lower in coffee forest through creating space for coffee production. We expect that these parameters will be lowest in silvopasture, due to removal of trees e.g. for fuelwood; (2) the number and size of canopy gaps and canopy openings are expected to be lowest in intact forest and plantation; and (3) 3D forest structure, measured as PAVD, will be highest in intact forest, for both understory and canopy. Coffee forest is expected to have a lower PAVD in the understory, but values similar to intact forest in the canopy. Silvopasture is expected to have the lowest PAVD values in both understory and canopy, while plantation has canopy PAVD values similar to intact forest, but a very low understorey PAVD.

2. Methods

2.1. Study site

The research was conducted in the montane cloud forests of the Kafa Biosphere Reserve in Ethiopia (36°3′22.51″ E, 7°22′13.67″ N – Fig. 1) which has an altitudinal range from 500 to 3500 m above sea level. The Kafa Biosphere Reserve is a hotspot for biodiversity with around 244 plant species, including 110 tree species, and over 300 mammal species (Mittermeier et al., 2004; NABU, 2014). The Kafa Biosphere Reserve is covered by more than 50% with forest, including 7% of protected intact forests and 48% of buffer zones or candidate core zones. About 45% of the Kafa Biosphere Reserve consists of agriculture and pasture. The candidate core zones include zones designated for coffee cultivation. Farmers producing coffee are doing so under a Participatory Forest Management (PFM) scheme. The idea behind the PFM scheme is to ensure a long-term source of income by sustainable management of forest resources.