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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.

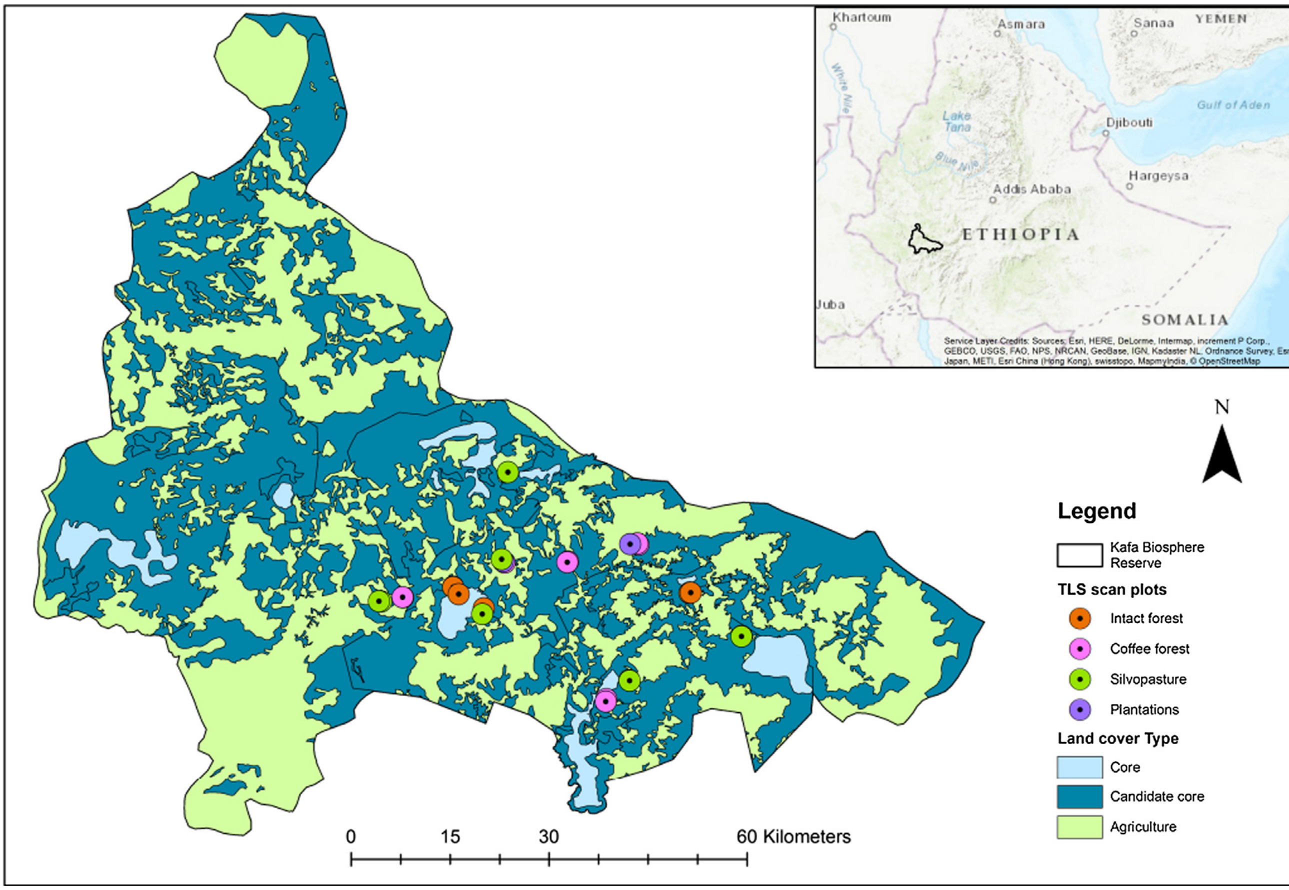

Fig. 1. The location of the Kafa Biosphere Reserve in Ethiopia and location of the plots.
Source: Dresen, 2011

2.2. Plot design and conventional measurements

Plots were selected according to a stratified sampling design. The stratification was based on an overlay between several GIS data layers: a fragmentation map (Mulatu, 2013), a land use/cover map (Dresen, 2011) and a topographic map. Within the four forest types, a total of 27 plots were established (Intact: 9 plots, coffee forest: 8 plots, silvopasture: 7 plots and plantation: 3 plots). From the 27 plots, 21 plots had a 20 m radius and six plots a 10 m radius due to difficult terrain (e.g. slope). We used a nested design, where all trees of ≥ 20 cm diameter at breast height (DBH) were measured for their diameter and identified to species in the 20 m (or 10 m) radius plot, while trees of 5–20 cm DBH were included within the centre 5 m-radius subplot only (Fig. 2B). Above-ground biomass (AGB) was derived from the DBH, species names and the wood density values for African tropical moist forests (Chave et al., 2009). Basal area (BA) and tree density were derived from the data. For an overview of all forest structural parameters derived from the TLS and conventional forest measures, including a detailed workflow on how the forest structural parameters were derived see Appendix A.

2.3. TLS measurements

A RIEGL VZ-400 terrestrial laser scanner (RIEGL Laser Measurement Systems GmbH, Austria) mounted on a tripod was used. The VZ-400 operates at a wavelength of 1550 nm and uses on-board waveform processing to record up to four returns per outgoing pulse with a range up to 350 m. For each plot, five scan positions were used: one in the centre and four in the cardinal directions (Fig. 2B). Cylindrical, retro-reflective targets (20 in total) were placed in the plot to allow co-registration of the individual point clouds (Wilkes et al., 2017). Pre-processing of the point cloud data was performed using RiSCAN PRO software (RIEGL Horn, Austria). Multiple scans per plot were co-registered based on their corresponding tie points using the 20 reflector targets from the field. Alignment errors were corrected using the multi-station adjustment (MSA) module, which improves the registration of the scan positions (Wilkes et al., 2017). Fig. 2C shows an example of the 2D equiangular projection of the co-registered TLS point cloud.

2.4. TLS derived parameters

Vertical profiles of Plant Area Volume Density (PAVD) were derived for 0.5 m vertical bins from ground level to top of the canopy using individual TLS scans based on the method developed by Calders et al. (2014) (Fig. 2A). The integral of PAVD over the whole canopy is the Plant Area Index (PAI) (Calders et al., 2015b). The retrieval method allows the estimation of PAI using multiple TLS returns and a height correction that accounts for sloped terrain. In short, the vertically resolved, directional gap fraction was estimated by relating the number of returned pulses to the total number of emitted pulses (Jupp et al., 2009). Next, PAVD was derived from the gap fraction at the hinge angle (57.5° zenith) to minimise the influence of leaf angle distribution (Jupp et al., 2009). The profiles can be aggregated into different height layers. In cases when one PAVD value per plot was needed, gap fractions of the single scans were averaged and then PAVD was derived. All plots are surrounded by forest of the same level of disturbance, to ensure PAVD (not limited to the 20 m radius) was representative for the plot.

To extract the canopy and canopy height parameters, the registered point clouds were loaded into CompuTree point cloud analysis open source software (Hackenberg et al., 2015). The detailed processing

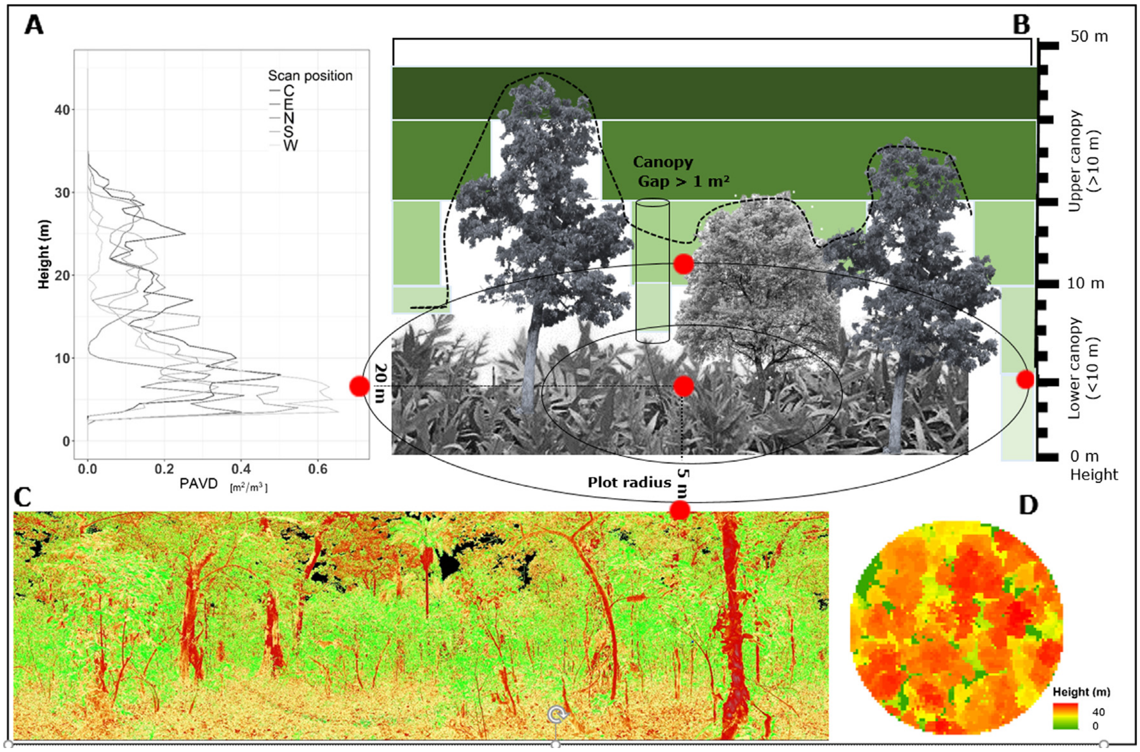

Fig. 2. Overview of the TLS derived parameters capturing forest structure. A: Example of the Plant Area Volume Density (PAVD) of one plot with the different scan positions. B: Canopy related parameters derived from the TLS Digital Height Model (DHM): Canopy height as the height of the vegetation (see dotted line); Canopy gap: number of canopy gaps with a size of > 1 m^2 and < 10 m height; Canopy openness: area of open space (seen from the top) relative to the highest tree in the plot at 5 m height intervals (indicated by the shades of green). Scan positions are indicated by red dots. C: 2D equiangular projection of the TLS point cloud (projections for each forest type can be found in Appendix B). D: DHM for a 20 m radius plot at 0.5 m resolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

steps can be found in Appendix A. The derived 2D canopy height models (DHM) were exported as 0.5 m resolution raster files and further analysed in ArcMap (ESRI Redlands USA) (Fig. 2D). The following parameters were derived from the DHM: (i) Canopy height: the top of the canopy at 0.5 m resolution for the 20 (or 10) m radius plot; (ii) Canopy gaps: defined here as neighbouring pixels with canopy height of < 10 m and with an area of ≥1 m^2 (Hunter et al., 2015). From the canopy gaps the maximum and mean gap area, and the number of gaps per plot were derived; (iii) Canopy openness, defined here as all empty spaces of ≥1 m^2 at 5 m height intervals, calculated until the maximum canopy height (Fig. 2B, green layers). With the canopy openness we do not capture the empty space underneath the upper canopy (this would be the inverse of the PAVD).

2.5. Statistical analysis

Linear mixed-effects models were used to compare the forest types for the conventional forest structure measurements (i.e. AGB, BA, tree density and the DBH distribution). The model selection was based on Akaike's Information Criterion, adjusted for small sample sizes (AICc). Models within 2 AICc-units from the model are equally supported (Burnham and Anderson, 2002). Similarly, we used linear mixed-effects models to compare TLS derived PAVD at 5 m height intervals among forest types. Mixed-effect models were used because multiple values (i.e. PAVD for each 5 m height interval) per plot are included, thus accounting for the fact that data points within a plot cannot be regarded as independent data points. We compared five models with varying fixed effects structures: (1) height interval, forest type and their interaction and including a random slope in height interval; (2) height interval, forest type and their interaction; (3) forest type; (4) height interval; and (5) only an intercept. In addition, we added a random slope for height interval to account for plot-to-plot variation in the relation between height interval and PAVD, which significantly improved model fit based on a likelihood-ratio test (see Appendix C). The same model comparison was used for the TLS derived canopy openness. Similarly, we compared the forest types for the TLS derived canopy height distribution, using mixed-effect models with a random intercept per plot, and compared the model with a model with a fixed intercept. Where needed, data were transformed (Appendix C) to enhance normality and homoscedasticity. All analyses were performed in R, version 3.3.3 (R core team); mixed-effects models were performed using the lme4 R package (Bates et al., 2014).

3. Results

3.1. Conventional forest structure parameters

Mean DBH, AGB and BA differed between forest types, but this was not the case for tree density (Appendix C). Predicted mean DBH values ranged from 62 ± 12 cm for intact forest (median = 40 ± 54.5 cm) to 34 ± 18 cm for plantation (median = 34.3 ± 15.5 cm). Coffee forest and silvopasture were similar with mean DBH values of about 46 ± 12 cm (median = 37.0 ± 31.8 cm and 33.5 ± 29.3 cm, respectively). Large trees (> 100 cm DBH) were most abundant in intact forest, and also present in coffee forest, although to a lesser extent (Appendix D). The DBH distributions show that trees with a DBH > 100 cm were almost absent in silvopasture and plantation, with plantation having many trees of 25–50 cm DBH (Appendix D). Mean BA and AGB were largest in intact forest (respectively 97 ± 28 m^2/ha and 753 ± 259 t/ha), followed by plantation (respectively 47 ± 49 m^2/ha and 422 ± 449 t/ha), coffee forest (respectively 40 ± 30 m^2/ha and 295 ± 275 t/ha) and silvopasture

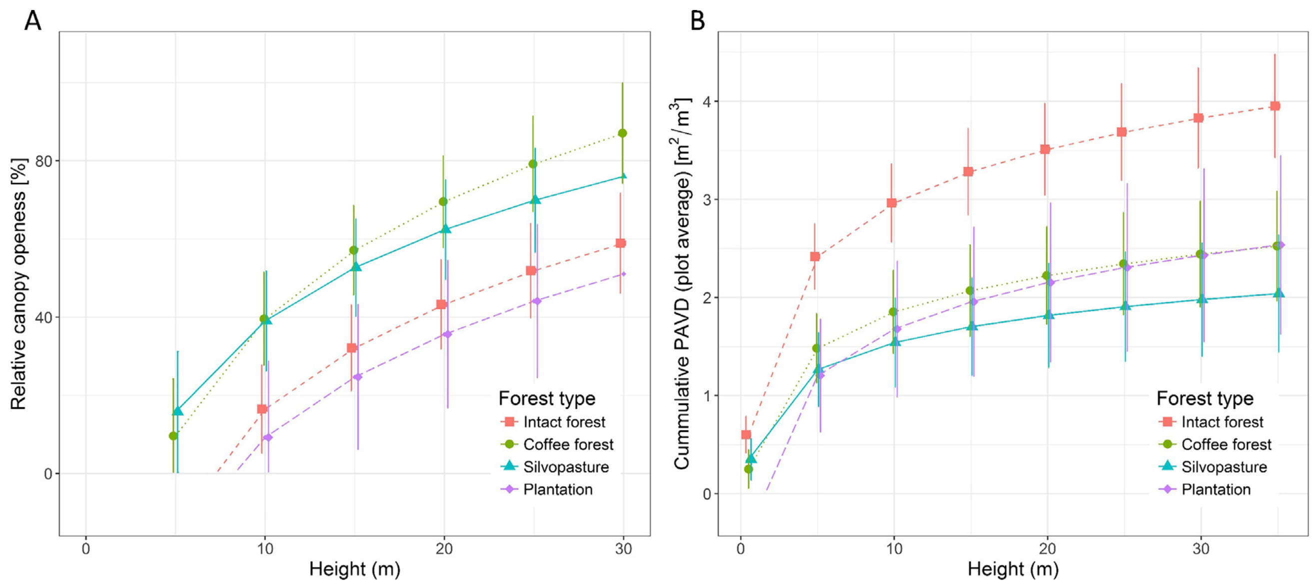

Fig. 3. A: Canopy openness per forest type at 5 m height intervals. B: Cumulative Plant Area Volume Density (PAVD) as a function of height across four forest types. Predicted values are indicated (± SE; n = 27 plots).

(respectively 33 ± 32 m^2/ha and 282 ± 294 t/ha). Although no significant effect of forest type was found, mean tree density followed the same order (intact forest > plantation > coffee forest > silvopasture) (Appendix D).

3.2. TLS derived canopy forest structure parameters

Canopy openness differed between forest types and was also influenced by height classes. Coffee forest had a lower canopy openness between 0 and 10 m compared to silvopasture, but had higher canopy openness in the higher height classes (predicted values range from 10% to 94% and 15% to 86%, respectively) (Fig. 3A; Appendix C). Intact forest and plantation had similar canopy openness (predicted values range from −9% to 63% and −17% to 57%, respectively).

Average canopy height, mean and maximum gap size, and the number of gaps also differed among forest types (Fig. 4; Appendix C). Canopy height was highest in plantation (26.4 ± 9.7 m), followed by intact forest (19.0 ± 4.7 m), while silvopasture and coffee forest had the lowest canopy heights (17 ± 5.3 m and 15.5 ± 5.6 m respectively) (Fig. 4A). Maximum gap size was higher in coffee forest and silvopasture (18.3 ± 4.6 m^2 and 19.8 ± 4.9 m^2, respectively) than in intact forest (7.5 ± 4.3 m^2) and plantation (2.7 ± 7.5 m^2) (Fig. 4C - square root transformed values). Similar differences were found for the mean gap size with the lowest values in plantation (0.8 ± 0.5 m^2), followed by intact forest (0.9 ± 0.3 m^2), silvopasture (1.8 ± 0.3 m^2) and coffee forest (2.0 ± 0.3 m^2) (Fig. 4B - log transformed values). Plantation also had the lowest number of gaps per plot (0.5 ± 0.8), followed by coffee forest (1.2 ± 0.5). The number of gaps was the highest in intact forest (1.5 ± 0.5) and silvopasture (1.3 ± 0.5) (Fig. 4D - log transformed values). However, gaps in intact forest were mainly small, with an average size of approximately 1.5 m^2 (equals 0.2 m^2 when log transformed).

3.3. TLS derived 3D Plant Area Volume Density (PAVD)

Plant Area Volume Density (PAVD) was generally highest in intact forest, for both understory and canopy compared to the other forest types (Fig. 5). In both coffee forest and silvopasture the variation in PAVD was high in the 0–10 m height range (Fig. 5A,B). In contrast to coffee forest and silvopasture, plantation consistently had very low PAVD values in the understory (Fig. 5A,B).

PAVD varied among forest types and height classes (Fig. 3B; Appendix C). The difference in PAVD is most apparent in the understory (< 10 m), with intact forest having most vegetation (estimated PAVD = 3.0 ± 0.4) and plantation the lowest amount of vegetation (estimated PAVD = 1.7 ± 0.7) (Fig. 3B). At a height of 35 m, intact forest reached an estimated PAVD of 4.0 ± 0.5, while plantation had an estimated PAVD of 2.5 ± 0.9. Coffee forest and silvopasture were very similar to each other in the understory (< 10 m) with the same estimated PAVD of respectively 1.9 ± 0.4 and 1.5 ± 0.4, but differed in the canopy (respectively 2.5 ± 0.6 and 2.0 ± 0.6) (Fig. 3B).

4. Discussion

4.1. Management impacts on forest structure and management implications

The conventional measures of AGB, BA and DBH differed among forest types (Berenguer et al., 2014; Clark and Clark, 2000), with highest values for intact forest (Appendix D). Unexpectedly, both AGB, BA and DBH were very similar for coffee forest and silvopasture. This means that in coffee forest not only the understory was cleared, but also many trees were removed, indicating a larger management impact than expected and also indicated by other authors (Aerts et al., 2011; Hundera et al., 2013; Schmitt et al., 2009). The large variation in BA and DBH in plantation is probably due to the different tree ages between the three forest plantation plots.

TLS estimated canopy openness was the lowest in plantation because the plantation plots consisted of even-aged monocultures, followed by intact forest. The higher canopy openness, and large canopy gaps, in coffee forest in comparison to silvopasture (especially ≥10 m, i.e. height above the coffee), contradicted the idea of coffee being produced underneath a relatively intact forest canopy. The high canopy openness in the investigated coffee forests suggested that canopy loss is much higher than the 30% canopy loss reported for nearby semi-coffee forests (Schmitt et al., 2009). Also canopy gap size (mean and maximum) was in line with these results of canopy openness. The large number of small gaps in intact forest could indicate canopy heterogeneity (i.e. multiple tree height levels). Such heterogeneity in canopy structure increases light levels in the understory, which is beneficial for the understory vegetation (Chazdon and Pearcy, 1991; Montgomery and Chazdon, 2001). Average canopy height was highest in plantation, but in contrast to our hypothesis, the differences between the intact

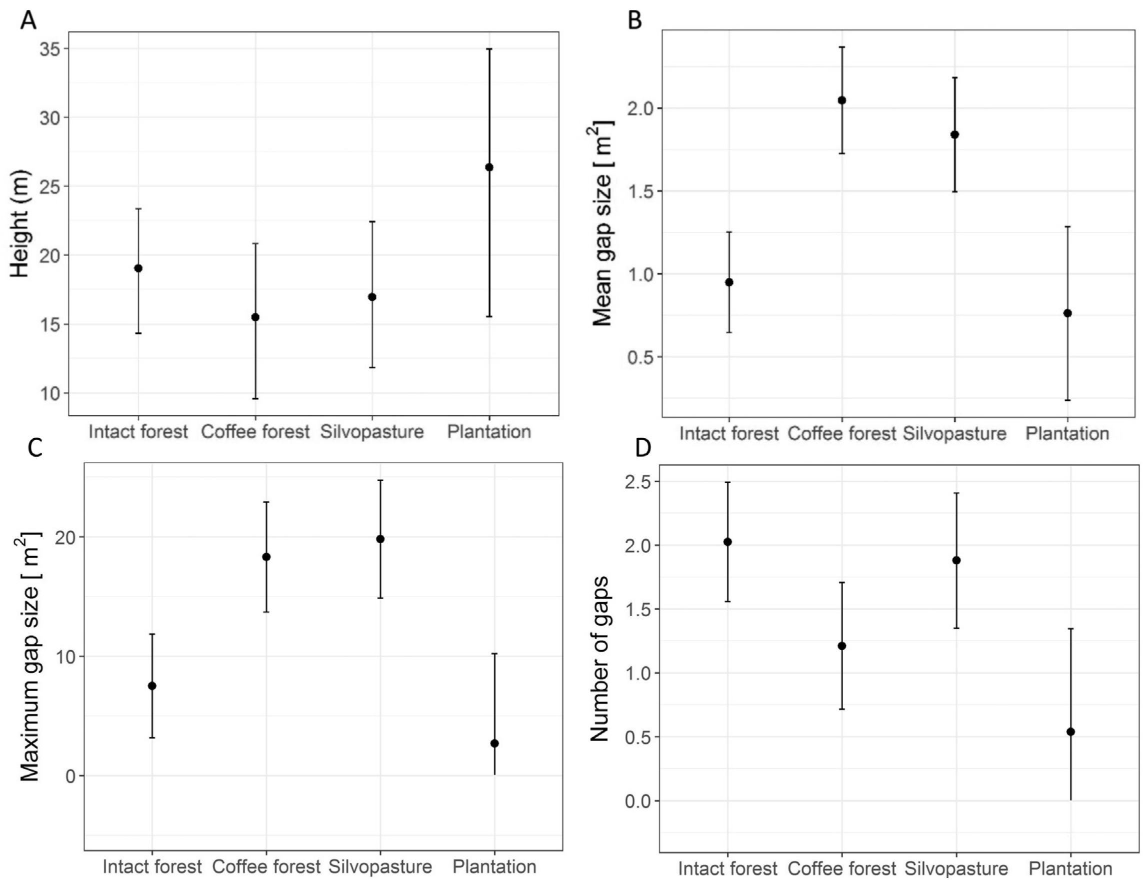

Fig. 4. Structural parameters derived from the Digital Height Model (DHM) at 0.5 m grid resolution for four forest types. A: Canopy height. B: Mean gap size (log transformed). C: Maximum gap size (square root transformed). D: Number of gaps (log transformed). Predicted values are indicated (± SE; n = 27 plots).

forest, coffee forest and silvopasture were small, probably due to the large variation between plots. Overall canopy height in coffee forest and silvopasture was the lowest, which could be detrimental for habitat heterogeneity and associated biodiversity (Ghazoul and Sheil, 2010; Martins et al., 2017).

The differences in 3D vegetation structure (PAVD) between forest types were significantly different for the different vegetation heights. Intact forest had, in general, the highest vegetation density over the complete height range. In addition to the conventional parameters and canopy gap parameters, the vegetation density in coffee forest at the canopy level (> 10 m) was lower than expected. Our assumption that coffee forest plots have a relatively intact canopy (intended to shade the coffee) was confirmed only for two out of the eight coffee forest plots (i.e. plot 10 and 11; Fig. 5B). As expected coffee forest had high vegetation density between 2 and 10 m due to the coffee plants. The PAVD in silvopasture partially confirmed our assumption of low vegetation density in the canopy, supported by large canopy gaps and low conventional parameters (DBH, AGB, BA and tree density). However, the understory vegetation in silvopasture was dense, most likely due to infrequent fuelwood collection and non-intensive grazing in most of the plots. Partial removal of the canopy enables light to reach the forest floor and creates a dense layer of heliophile species (M. Decuyper, personal observation). Cuni-Sanchez et al. (2016) found similar results for PAVD along a successional gradient in colonizing forest and young successional forest in Gabon. In all plantation plots there was little understory (indicated by the very low PAVD values), probably due to clearance of the vegetation and/or lack of sunlight. Tripathi and Singh (2009) identified similar patterns comparing vegetation structure from natural forests to plantations. Plantations could therefore be seen as structurally poor and offering only few habitat niches for flora and fauna (Tews et al., 2004).

Most parameters, both conventional and TLS derived, followed our prior expectations, but the forest structure of coffee forest did not. The high canopy openness together with the low BA estimations, and our field experiences (M. Decuyper, personal observation) in coffee forest warrant more tangible measures for sustainable forest management of coffee forest under the PFM certification, such as thresholds on canopy cover (Aerts et al., 2011; Hundera et al., 2013). Currently, large differences exist between PFM rules and regulations and objectives of policy makers on the one hand, and the interpretation and implementation of sustainable forest management in PFM sites by local communities on the other (Ayana et al., 2017). More tangible measures could relieve concerns regarding sustainability of the PFM scheme and the produced coffee, currently leading to heavy degradation and severely jeopardizing the sustainability of the coffee production, the diversity of wild coffee varieties, and ecosystem resilience (Aerts et al., 2011; Ayana et al., 2017).

4.2. TLS monitoring helps determining management impacts on 3D forest structure

While habitat loss through forest area loss and forest fragmentation is relatively easy to monitor and demonstrate, small scale changes in forest structure due to forest management (a more internal qualitative habitat loss) is much more difficult to monitor (Mitchell et al., 2017). The impact of small scale forest management (as is the case in this study area) mainly affects the understory while the canopy is left relatively intact, making such forest alterations undetectable by current satellites (Mitchell et al., 2017).

TLS measurements captured the variation in vegetation structure in the understory and canopy for different forest types. These TLS measurements enabled 3D quantification of forest structural measurements

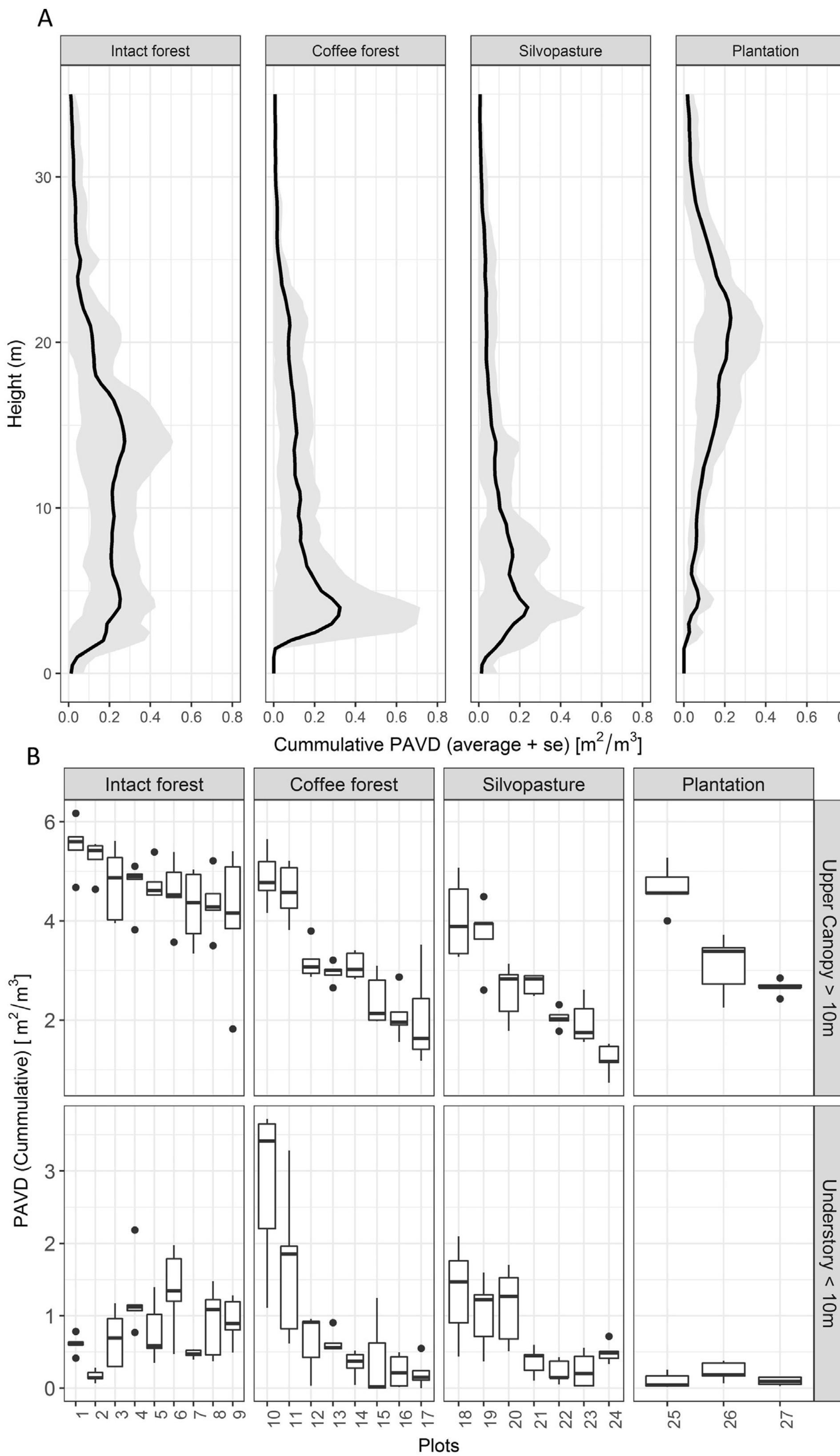

Fig. 5. A: Mean Plant Area Volume Density (PAVD) and standard error (SE – shaded area) for all plots per forest type. B: Boxplots, with the median (horizontal line) lower and upper quartiles (hinges), presenting the maximum PAVD at plot level and its variation (different scan positions within the plots), for the canopy (> 10 m) and understory (< 10 m) (vertical panelling) along the different forest types (horizontal panelling).

such as PAVD, but also the 2D canopy gaps and canopy openness at different heights to evaluate the effect of management implications. These parameters could potentially be used for habitat heterogeneity proxies and linked to biodiversity analysis (Tews et al., 2004; Zipkin et al., 2009). Several of these parameters cannot be measured by conventional forest inventories, such as 3D position of plant volume (quantified by PAVD) and open spaces (i.e. inverse of PAVD). The 3D leaf positioning is important as it influences light extinction, tree architecture and photosynthetic leaf traits (e.g. Montgomery and Chazdon, 2001). Open space in different forest layers, including the forest understorey, is of great importance for many flora and fauna (Chazdon and Pearcy, 1991; Zahawi et al., 2015). With TLS, open spaces can be measured by assessing canopy openness and gaps at different heights. For example, open spaces and light between 0 and 1 m is highly important for seedling germination (Chazdon and Pearcy, 1991), at 0 and 5 m for coffee plants and their pollinators (i.e. bees) (Aerts et al., 2011), while between 5 and 30 m this can be important for bird species and epiphytes (Zahawi et al., 2015). For quantifying management effects on forest structure, consistent monitoring of changes in 3D structure is needed and here TLS is clearly an add-on or an alternative for monitoring conventional forest structure parameters. TLS is also an add-on for small scale canopy gap research, as it fills a gap between conventional geometric gap measurements (Van der Meer et al., 1994), grid-based top of canopy measures (Hubbell and Foster, 1986), hemispherical cameras (Jonckheere et al., 2004) and airborne or satellite data (Joshi et al., 2015b).

Besides the capability of TLS of measuring stem based structural parameters (i.e. AGB, BA, DBH and tree density) (Gonzalez de Tanago et al., 2018), there is still a need for the development of operational TLS data processing tools since there is not yet a fully automated way to measure DBH, AGB and BA in tropical forests. For example, deriving structural parameters such as biomass for tropical forests is quite challenging due to the dense understory (Gonzalez de Tanago et al., 2018). Additionally, from a forest conservation perspective, TLS cannot capture information on tree species richness in tropical forests, thus there is a need for integrating different data sources in order to fully understand the forest structural diversity. Complementing conventional parameters with TLS derived parameters shows potential in describing the sometimes subtle differences in forest management.

TLS derived structural parameters can benefit from further integration with other datasets to better characterize forest structural differences across spatial scales (van Leeuwen and Nieuwenhuis, 2010). Not only data from conventional forest inventory methods, but also space borne and airborne LiDAR (Brede et al., 2017), multispectral TLS, as well as satellite remote sensing derived structural parameters are important to consider. Several studies have investigated the potential integration and upscaling opportunities of LiDAR and satellite remote sensing data, for example for stand height estimation (Mora et al., 2013). Further research is needed to link other TLS derived parameters with conventional forest inventory data, satellite or airborne data (Pettorelli et al., 2014) for better monitoring of management impacts on forest structure and biodiversity.

Authors' contributions

M.D., K.M., B.M., J.C., L.K., M.H. and F.B. conceived the idea. M.D., K.M., B.B., K.C. and J.A. performed the computations. D.R. verified the analytical methods and D.R., J.C., L.K., M.H. and F.B. supervised the development of this work. All authors interpreted the results and contributed to the final manuscript and M.D. led the writing of the manuscript. All authors gave final approval for publication.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2018.07.032.

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