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Terrestrial laser scanning for non-destructive estimates of liana stem biomass

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ABSTRACT

Lianas are important and yet understudied components of tropical forests. Recent studies have shown that lianas are increasing in abundance and biomass in neotropical forests. However, aboveground biomass estimates of lianas are highly uncertain when calculated from allometric relations. This is mainly because of the limited sample size, especially for large lianas, used to construct the allometric models. Furthermore, the allometry of lianas can be weakly constrained mechanistically throughout its development from sapling to mature form. In this study, we propose to extract liana stem biomass from terrestrial laser scanning (TLS) data of tropical forests. We show good agreement with a concordance correlation coefficient (CCC) of 0.94 between the TLS-derived volume to reference volume from eleven synthetic lianas. We also compare the TLS-derived biomass for ten real lianas in Nouragues, French Guiana, with the biomass derived from all existing allometric equations for lianas. Our results show relatively low CCC values for all the allometric models with the most commonly used pantropical model overestimating the total biomass by up to 133% compared to the TLS-derived biomass. Our study not only facilitates the testing of allometric equations but also enables non-destructive estimation of liana stem biomass. Since lianas are disturbance-adapted plants, liana abundance is likely to increase with increased forest disturbance. Our method will facilitate the long-term monitoring of liana biomass change in regenerating forests after disturbance, which is critical for developing effective forest management strategies.

1. Introduction

Accurately quantifying the aboveground biomass (AGB) of forests is essential to understand the role forests play in the global carbon cycle. Tropical forests are major carbon sinks and yet the amount of carbon stored is highly uncertain. In addition, tropical forests are undergoing large-scale structural changes due to anthropogenic disturbances such as increased atmospheric CO2, logging, hunting, and conversion of forested areas into agricultural lands (Crowley, 2000; Woods, 1989; Wright, 2005). One such structural change in tropical forests is the increase in liana abundance and biomass in the Neotropics (Phillips et al., 2002). Lianas are woody climbing plants that use trees and other plants as structural support for ascending to the canopy (Schnitzer et al., 2002). Increase in liana abundance results in reduced tree growth and increased tree mortality thereby playing an important role in regional and global carbon cycle (Putz, 1984; Schnitzer et al., 2000; Van Der Heijden et al., 2016). Since lianas are disturbance-adapted plants, liana abundance is likely to increase with increased forest disturbance, thereby increasing tree mortality and decreasing tree growth (Van Der Heijden et al., 2016; Campbell et al., 2018). Tyman et al. (2016) showed that liana infested patches in an old-growth tropical rainforest in central French Guiana had an AGB stock 58% lower than that of the high-canopy forest.

Despite the increasing liana abundance, importance of lianas for forest functioning and productivity is often overlooked as they are thought to contribute negligibly to woody structure and biomass. Moreover, liana removal is a common timber management practice (Gourlet-Fleury and Beina, 2013). However, biomass and productivity of forests could be underestimated by ignoring the contribution of lianas (Gerwing and Farias, 2000). Few studies have established allometric equations for estimating liana biomass by destructive harvesting (Gehring et al., 2004; Schnitzer et al., 2006; Patrick, 2013a; Addo-
Fordjour and Rahmad, 2013b). Depending on the choice of the allometric equation, the contribution of liana biomass to total aboveground biomass has been estimated to range between 3% and 17% across different tropical forests (Jérôme Chave et al., 2003; Liddell et al., 2007). Van Der Heijden et al. (1326) have shown that increased liana abundance decreased the aboveground carbon uptake by 76% and lianas biomass has been estimated to range between 3% and 17% across different tropical forests (Fernández, Brazil, Venezuela, Cambodia). This is a relatively low amount compared to the pantropical allometry for trees. For example, Jérôme Chave et al. (2006) established new allometric equations for lianas from Malaysia and reported that the pantropical allometric equation from Schnitzer et al. (2014) used 4004 destructively harvested individuals to establish the most commonly used pantropical allometry. Recently Patrick (2013a) established new allometric equations for lianas from Malaysia and reported that the pan-tropical allometric equation from Schnitzer et al. (2006) overestimated the liana biomass by as much as 44% at their sites. Miao et al. (2016) showed that the liana biomass from five commonly used allometric relations produced disparate results, making the choice for the right biomass equation more difficult. Therefore, it is important to develop methods to determine liana biomass reliably. Throughout the manuscript, aboveground woody biomass of lianas is referred to as liana biomass or AGB, unless otherwise specified.

Almost all liana allometric models established to date are based on diameter only, except for the ones proposed by Gehring et al. (2004), which included length in addition to diameter. Schnitzer et al. (2006) showed that diameter is not a good predictor of biomass of lianas and Gehring et al. (2004) showed that the equation using both length and diameter as estimators outperformed the allometry based only on diameter. This is not surprising, as lianas are known for their rapid rates of growth in length and relatively slower rates of growth in diameter (Putz, 1990). However, it is almost impossible to measure liana length using conventional methods in the field and as a result highly inaccurate allometric equations using diameter are widely used. Another major limitation of the current allometric equations for liana biomass is the lack of data from larger lianas. Despite being few in numbers, large lianas represent a large fraction of the total liana biomass. Large lianas are much more dynamic than large trees with their long-term annual woody turnover rates five to eight times those of trees. As a result, large lianas play an important role in the carbon cycle (Phillips et al., 2005). In addition, studies have indicated that liana biomass is increasing across the entire neotropics (Phillips et al., 2002; Wright et al., 2004; Schnitzer and Bongers, 2011). Accurate quantification of liana biomass is necessary not only to better understand the role lianas play in the tropical forest carbon cycle but also to estimate how much of the tree biomass displaced by lianas is replaced by them. Besides, in global vegetation models including lianas, estimates of liana biomass from the adopted existing allometric relations are an important source of uncertainty (di Porcia and Brugnara et al., 2019).

It is widely accepted that there is a need for larger sample size of destructively harvested lianas across all size classes to establish more accurate allometric equations for deriving liana biomass (Miao et al., 2016; Schnitzer et al., 2006). Large sample size is also necessary to test if it is even possible to establish an allometric model for liana AGB considering the weak link between its stem structure and development from sapling to mature form, both evolutionarily and mechanically (Schnitzer et al., 2006). Given the variable growth forms of lianas, it is impossible to destructively harvest lianas without causing considerable damage to the trees that host them. In addition, damage to a tree with inter-crown liana connections could damage the neighboring trees (Vidal et al., 1997). For instance, Gerwing (2001) used a combination of tree felling and climbing trees to cut the liana-bearing branches to obtain the harvested lianas in their entirety. However, recent advances in remote sensing technologies have enabled us to view the forest structural complexity in new and unprecedented ways. Terrestrial laser scanning (TLS) is an active remote sensing technique and can measure various forest structural parameters with high spatial accuracy. Calders et al. (2015) proposed non-destructive ways of estimating tree AGB from TLS data. Despite the increasing importance of lianas, few studies have attempted to quantitatively study liana structure and biomass. Since TLS derived volume estimates do not assume any prior information about the structure and size of lianas, they can yield direct estimates of volume compared to the allometric equations.

Our study aims to test the potential of the emerging TLS technology to estimate liana woody biomass. We present a method to estimate individual liana stem volume from 3D TLS data of tropical rainforests. The presented method is built on the TreeQSM algorithm, originally developed for estimating tree volume (Raumonen et al., 2013). Given the difficulty of destructively harvesting a liana in its entirety, we used synthetic lianas to validate the presented method. This enables a more accurate validation of the method than the validation with real lianas. We also compared the TLS-derived biomass estimates of ten real lianas ranging in diameter from 4 to 28 cm with the estimates from different allometric equations. TLS can only estimate the stem volume and hence the woody biomass of lianas. We mention explicitly in the text when the allometric-derived estimates, against which we compare our TLS-derived biomass estimates, include both wood and leaf components.

The specific objectives of the study are the following:

1. To develop a new method for deriving individual liana volume estimates from 3D TLS data
2. To validate the accuracy of the TLS-derived volume against the actual volume using synthetic lianas
3. To compare the TLS-derived biomass estimates with allometric-derived estimates for real lianas in the field
4. To analyze the sources of error and uncertainty when using TLS to estimate liana stem biomass in the field

2. Materials and methods

2.1. Study area and data collection

We collected TLS data from both synthetic lianas and real lianas in the forest. TLS data from synthetic lianas were collected from the trees close to the field station and in the forests on Barro Colorado Island (BCI), Panama. TLS data from real lianas were collected from an old growth forest in the Nouragues Ecological Research Station of French Guiana. We used a RIEGL VZ400 (for synthetic lianas) and a RIEGL VZ1000 (for real lianas) terrestrial laser scanner, which are multiple return time-of-flight based scanners using a narrow infrared laser beam of wavelength 1550 nm and a beam divergence of 0.35 mrad, to collect liana data. The scanner was mounted on a tripod at approximately 1.3 m from the ground and used an angular sampling resolution of 0.04°. The acquisition time for one full scan with an angular resolution of 0.04° is 4 min 12 s for both scanners. Based on the manufacturer’s specifications, the data from the two scanners are interoperable (Calders et al., 2017).

2.1.1. Synthetic lianas

We made eleven synthetic lianas using a combination of multiple ropes and flexible PVC (polyvinyl chloride) tubes (see Fig. 1). These ropes were wrapped around multiple tree branches in order to simulate real field-like conditions, where lianas are often occluded by tree branches. We also put the synthetic lianas on multiple trees as lianas can have more than one host tree in the field. These synthetic lianas ranged in diameter from 1 to 3 cm and in length from 7 to 25 m (Table 1). In addition, variation in diameter within an individual synthetic liana was introduced by combining different components (the tubes and/or ropes) of decreasing diameter along increasing length of the liana. The diameter reported in the table for each of the synthetic
Lianas is the diameter at 1.3 m from the starting point on the ground. The volume was calculated from the diameter \( d \) and length \( l \) of each of the components used to make the synthetic liana using the formula: \[ V = \pi \frac{d^2}{2} l \], where \( i \) is the number of components. For example, liana No. 10 in Table 1 was made from five different components of diameters 1, 1.3, 1.5, 2.5, and 4 cm with respective lengths of 4.35, 2.22, 5, 2.15, and 3.5 m.

Ten of the eleven lianas were put on trees that were reachable by a ladder (reaching a maximum height of 6 m from the ground) close to the field station on Barro Colorado Island (BCI) in Panama and the eleventh liana (a climbing rope) was shot into a tree (reaching a height of 12 m from the ground) in the old-growth forest on BCI using a slingshot. After putting the lianas on trees, TLS data were collected from these synthetic lianas following a radial pattern around the lianas. The location and the number of scan positions for each liana were chosen to minimize occlusion depending on the understory vegetation as suggested in Wilkes et al. (2017).

As mentioned above, we used flexible PVC tubes and ropes to make the synthetic lianas. While the tubes ranged in diameter from 1.5 to 3 cm, the ropes used were 1 to 1.3 cm in diameter and moved often between two scan positions resulting in a noisy point cloud after registration. Though TLS data from single scan position leads to occlusion with some missing liana segments (depending on which scan position was used), it results in a point cloud with no post-registration noise. As a result, we compared the results from multi-scan and single scan TLS data for all the eleven synthetic lianas. We chose the single scan position resulting in minimal occlusion (which is still significantly higher than a multi-scan TLS data (Bauwens et al., 2016)) and thus having fewer missing liana segments, for the single scan TLS data.

### Table 1

<table>
<thead>
<tr>
<th>Liana no</th>
<th>Diameter (cm)</th>
<th>Length (m)</th>
<th>Volume (L)</th>
<th>No. of host trees</th>
<th>Height from the ground (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>18.50</td>
<td>1.45</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>11.75</td>
<td>0.92</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>1.22</td>
<td>25.50</td>
<td>2.98</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>1.30</td>
<td>18.75</td>
<td>1.85</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>1.30</td>
<td>14.00</td>
<td>1.86</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>1.50</td>
<td>10.60</td>
<td>1.34</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>1.50</td>
<td>13.35</td>
<td>1.62</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>1.50</td>
<td>7.22</td>
<td>1.17</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>2.50</td>
<td>9.37</td>
<td>2.23</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>3.00</td>
<td>17.22</td>
<td>5.05</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>11</td>
<td>3.00</td>
<td>9.50</td>
<td>4.12</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 2
Detailed information for each of the real lianas scanned by the Terrestrial Laser Scanner (TLS). Liana height refers to the maximum height reached by the liana points from the ground.

<table>
<thead>
<tr>
<th>Liana no</th>
<th>Diameter (cm)</th>
<th>Liana height (m)</th>
<th>Host canopy height (m)</th>
<th>Wood density (g/cm³)</th>
<th>No of scan positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.9</td>
<td>21.7</td>
<td>31.2</td>
<td>0.40</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>4.6</td>
<td>16.3</td>
<td>26.0</td>
<td>0.67</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>5.1</td>
<td>21.1</td>
<td>32.5</td>
<td>0.64</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>6.0</td>
<td>24.0</td>
<td>29.7</td>
<td>0.56</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>6.2</td>
<td>23.8</td>
<td>26.9</td>
<td>0.60</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>10.2</td>
<td>26.2</td>
<td>33.6</td>
<td>0.43</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>10.8</td>
<td>26.0</td>
<td>32.8</td>
<td>0.51</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>16.2</td>
<td>20.6</td>
<td>29.0</td>
<td>0.39</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>20.2</td>
<td>24.0</td>
<td>32.6</td>
<td>0.47</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>28.3</td>
<td>32.4</td>
<td>39.7</td>
<td>0.49</td>
<td>9</td>
</tr>
</tbody>
</table>

Riddet et al., 2010). It should be noted that this is the first study to derive wood density estimates of lianas from micro-cores and there is no good benchmark for micro-core derived densities in general and for liana samples in particular. Table 2 shows the detailed information for each of the scanned lianas. TLS data from all the ten lianas and their corresponding host canopies are shown in Appendix A.2.

2.2. Liana biomass estimation from TLS data

The registration of data from all scan positions for each of the lianas (both synthetic and real) was done using the RISCAN Pro software (version 2.5.3, RIEGL Laser Measurement Systems GmbH, Horn, Austria) provided by RIEGL. Algorithms exist for automatic or semi-automatic extraction of tree stems from a plot-level data of temperate or tropical forests (Burt et al., 2018; Raumonen et al., 2015). In these algorithms, tree stems are first detected and these stem points are used as seed points for extracting the full tree. For an automatic or semi-automatic liana extraction algorithm to work, liana stem locations should be first detected. Unlike for tree stems, algorithms for automatic detection of liana stems from TLS data are complicated because of their small size and variable growth forms. As a result, all lianas (both synthetic and real) were manually extracted from the TLS data with the help of the software CloudCompare (Girardeau-Montaut, 2011), a process which took multiple hours per liana. We extracted the liana stems from the ground all the way up to the canopy of their host trees. In dense canopies, it was not always possible to extract the lianas all the way up to the top owing to occlusion and sensor limitations. The minimum size of the object resolvable by the scanner increases with increasing distance from the scanner, making it harder to extract small liana branches higher up in the canopy. We have shown the height up to which the lianas could be extracted from the TLS data with respect to their host canopy heights (see Table 2 and Appendix A.2). While we could follow the lianas ≤5 cm only up to an average of 65% of their host tree height, we were able to follow the large lianas all the way up to 80% of their host tree height. Once all lianas were extracted from the point cloud, we estimated their volume by applying a modified version of TreeQSM algorithm. The original algorithm is explained in detail in Raumonen et al. (2013) and Calder et al. (2015). The method was originally developed and successfully applied to derive volume estimates for trees (Calder et al., 2015; Gonzalez de Tanago et al., 2018). The method segments a given tree point cloud into stem and individual branches. Then it reconstructs a QSM (Quantitative Structure Model) by fitting cylinders to the segmented stem and branch data. From these QSMs, it is possible to compute various geometrical properties of trees such as diameter, length, volume, etc. For example, the total volume of a tree is the sum of volume of all cylinders fitted to the tree. In this paper, we pre-processed the liana point clouds and optimized some parameters of TreeQSM to derive liana volume estimates. Because lianas are structurally similar to trees, QSMs as hierarchical collections of cylinders are suitable for modeling lianas. Furthermore, TreeQSM is also suitable for liana QSM reconstruction as it does not have prior assumptions about the size, structure or species of lianas.

Liana biomass was then estimated from the wood density and QSM-derived volume estimates. The individual wood density estimates for each scanned liana were calculated from the micro-cores collected from the same individual (see Table 2).

2.2.1. Pre-processing steps

TreeQSM’s segmentation process starts from the base of a tree to correctly segment the tree into its main stem and branches. TreeQSM assumes that the base is at the bottom of the point cloud and can be automatically and accurately separated from the point cloud. If there are branches that touch the ground, the selection of the base may fail and thus the segmentation process can fail. Lianas have variable growth forms in the sense that they can branch out and some branches can loop back to the ground which violates TreeQSM’s assumptions. As a result and because we were mainly interested in the volume of the lianas, instead of applying TreeQSM to the entire liana, we manually segmented the parts that looped back to the ground, treated them as two different lianas and generated two different QSMs. We aggregated the volume from these two QSMs to get the final liana volume (see Fig. 3).

2.2.2. Input parameter optimization

We optimized the following parameters of TreeQSM: PatchDiam2Min, PatchDiam2Max and lCyl. The first two parameters define the size of the cover sets and the third parameter defines the relative length of the fitted cylinder with respect to the radius. The smaller the value of PatchDiam2Min and PatchDiam2Max, the smaller the fitted cylinders are, especially at the branches. The higher the value of lCyl, the longer the cylinders are and thus more robust to the noise.

We defined a range of values for these three parameters.

- PatchDiam2Min: 5 mm to 10 cm with an increment of 2 mm
- PatchDiam2Max: 6 mm to 12 cm with an increment of 2 mm
- lCyl: 3, 4, 5, 6, 7

We ran ten model iterations for each parameter combination. The reason for running more than one model iteration for a given parameter setting was because the generation of cover sets is random and every run with the same parameter setting would result in a model different from the previous run. The optimal parameter values were finally selected based on the following criteria:

- We calculated the diameter of trunk or main stem (see Fig. 6B) at various places along the length of the trunk by fitting least squares circles to the trunk point cloud. We compared the diameter from least squares circle fitting to the point cloud to the corresponding diameter estimated from cylinder fitting by TreeQSM at different places along the stem for all different parameter settings as follows

\[
d_{diff} = \frac{\min(\text{cloud}_d, \text{model}_d)}{\max(\text{cloud}_d, \text{model}_d)}
\]

(1)

We used the following condition based on \(d_{diff}\) as one of the criteria to select the optimal parameter setting (as in Calder et al. (2018)).

\[
d_{diff} < (d_{diff \_ max} * 0.95)
\]

(2)

- We computed the average distance between the point cloud and the fitted cylinders by TreeQSM for all parameter settings (\(pm\_dist\)) and checked if \(pm\_dist\) of the current parameter setting was within one standard deviation of the average \(pm\_dist\) of all the settings (as in 3).
We also computed the variance of the final volume from TreeQSM across ten different model runs generated for all parameter settings \( \text{var}_{\text{vol}} \) and checked if \( \text{var}_{\text{vol}} \) of the current parameter combination was less than two times the \( \text{var}_{\text{vol}} \) from all parameter settings (as in (4)) (see (Andrew Philip Burt, 2017) for more details on this criteria).

\[
\text{var}_{\text{vol}} < (\text{var}_{\text{vol}} \times 2)
\]

We combined all three above-mentioned criteria (Eq. (2)–(4)) to select the optimal parameter setting for generating the model. Once the optimal parameter combination was found, geometrical properties such as liana length and volume were computed as an average from the ten model runs for the chosen parameter combination. When multiple parameter combinations satisfied the above-mentioned optimal condition, we visually assessed the quality of the model fit to the point cloud in CloudCompare software to choose the best fit. When there was no parameter combination resulting in the optimal fit, we choose the model with the lowest point-model distance.

### 2.2.3. Extrapolation of missing liana volume

For real lianas in the field, it was not always possible to follow them all the way to the top because of occlusion from other vegetation in the canopy. This was true especially for smaller lianas (<5 cm diameter) (see Appendix A.2). We assessed the missing volume for all the branches, including the main trunk, of those lianas that we could not follow up to their tip by linearly extrapolating their stem (and branch) taper curve up to a minimum of 1 mm. The stem and branch taper curve is estimated from the cylinders fitted to the whole liana by TreeQSM algorithm.

The volume of the missing part of a liana branch was calculated using the Eq. 5.

\[
\text{Volume} = \frac{1}{3} \pi (r_1^2 + r_2 \cdot r_2 + r_2^2)h
\]

where \( r_1 \) is the radius of the fitted cylinder at the maximum length of a given liana branch, \( r_2 \) is 1 mm and \( h \) is the missing length of that branch detected by extrapolation.

---

**Table 3**

Different existing allometric equations for liana AGB (aboveground biomass) estimation used in this study. \( D \) refers to diameter measured at 1.3 m from the rooting base and \( D_{30} \) refers to diameter measured at 30 cm from the rooting base of lianas.

<table>
<thead>
<tr>
<th>Region</th>
<th>Allometric equation</th>
<th>Sample size</th>
<th>Aboveground components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Amazonia&lt;sup&gt;a&lt;/sup&gt;</td>
<td>( \exp(6.105+1.413\ln(D_{1.3}+0.997\ln(D_{30}))) )</td>
<td>439</td>
<td>Leaf and wood</td>
</tr>
<tr>
<td>French Guiana&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( \exp(-1.499+2.566\ln(D_{1.3})) )</td>
<td>85</td>
<td>Leaf and wood</td>
</tr>
<tr>
<td>Pantropical_no_ven&lt;sup&gt;c&lt;/sup&gt;</td>
<td>( \exp(-1.07+2.93\ln(D_{1.3})) )</td>
<td>407</td>
<td>Leaf and wood</td>
</tr>
<tr>
<td>Pantropical_all&lt;sup&gt;c&lt;/sup&gt;</td>
<td>( \exp(-1.05+2.75\ln(D_{1.3})) )</td>
<td>424</td>
<td>Leaf and wood</td>
</tr>
<tr>
<td>Malaysia&lt;sup&gt;d&lt;/sup&gt;</td>
<td>( 2.96+1.086\log(D_{1.3}) )</td>
<td>60</td>
<td>Only wood</td>
</tr>
<tr>
<td>Ghana (Primary)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>( 1.84+0.41\log(D_{1.3}) )</td>
<td>22</td>
<td>Only wood</td>
</tr>
<tr>
<td>Ghana (Secondary)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>( 0.31+1.15\log(D_{1.3}) )</td>
<td>24</td>
<td>Only wood</td>
</tr>
</tbody>
</table>

<sup>a</sup> (Gehring et al., 2004)  
<sup>b</sup> (Schnitzer et al., 2006)  
<sup>c</sup> (Patrick, 2013a)  
<sup>d</sup> (Addo-Fordjour and Rahmad, 2013b)
2.3. Liana biomass from allometric equations

We calculated liana biomass using seven different allometric equations as shown in Table 3. Of the seven equations, only one equation included length along with diameter (Gehring et al., 2004). All other equations were based on diameter only. Also, we indicated which allometric equations include both wood and leaf components in their biomass estimates. We defined length of a liana as the total length of the stem including all the branches. However, it is unclear how the length was defined in the allometric model of Gehring et al. (2004).

Unlike other allometric models, the allometric model proposed in Gehring et al. (2004) was based on diameter measured at 30 cm from the rooting base of lianas (see Table 3). Since we measured liana diameter at 1.3 m from the rooting base in the field (following the protocol in Schnitzer et al., 2006), we used the conversion equation proposed in Schnitzer et al. (2006) to convert the diameter at 130 cm to diameter at 30 cm. Pantropical_no_ven refers to the allometric equation established from four forest sites including two sites from Brazil, one from French Guiana and one from Cambodia. In addition to the above mentioned four sites, pantropical_all also includes lianas from a site in Venezuela. Schnitzer et al. (2006) provided a separate allometric model, Pantropical_no_ven, without the Venezuelan site, as the parameter estimates for this site differed significantly from the other four sites.

2.4. Comparison of methods

We used linear regression to compare the different methods for deriving length, volume, and biomass. We compared the TLS-derived length and volume to the reference length and volume for synthetic lianas by calculating the Root Mean Squared Error (RMSE) and concordance correlation coefficient (CCC) (Lawrence and Lin, 1989). RMSE evaluates how much the TLS-derived metrics deviate from the reference metrics. CCC computes the agreement of two different methods on a continuous scale and ranges from −1, meaning perfect disagreement, to +1, meaning perfect agreement. We compared the TLS-derived biomass against biomass estimated from the allometric equations in Table 3 by calculating ordinary least-squares regression and CCC.

3. Results

3.1. Liana volume estimation from QSM

TreeQSM algorithm required multiple parameters to be tuned and the best parameter combination for cylinder fitting to a liana was selected based on a combination of three criteria (see Fig. 4 and 5 to understand how these criteria resulted in a good fit after parameter optimization).

Smaller PatchDiam2Max values results in a less reliable QSM model for big liana segments (≥5 cm) (see Fig. 5A and B). Whereas for small liana segments, bigger PatchDiam2Max values results in the over-estimation of the segment volume (see Fig. 5C and D).

Besides parameter optimization, we estimated the potential missing parts of a liana stem and branches, mainly due to occlusion in the canopy, by linearly extrapolating the stem tapering estimated from TreeQSM algorithm for real lianas in the field (see Fig. 6). We used this extrapolation only to get an estimate of the missing liana volume and not for liana length or height.

3.2. Validating liana volume estimates with synthetic lianas

We compared the TLS-derived length and volume from both multi-scan and single-scan TLS data with the reference length and volume respectively for the eleven synthetic lianas (Fig. 7). In general, TLS-derived length and volume agreed well with reference length and volume with a CCC of 0.93 and 0.94 respectively for the multi-scan TLS data. While TLS-derived length agreed well with reference length with a CCC of 0.95 for the single scan TLS data, its TLS-derived volume had a lower CCC of 0.82 and higher RMSE of 0.77 L (compared to 0.45 L for the multi-scan data). In addition, as the results indicate, length was overestimated on average for both single and multi-scan TLS data by 7.4% and 10.9% respectively and volume was overestimated on average by 15.5% for the multi-scan data and underestimated on average by 8.1% for the single-scan data. The multi-scan and single-scan TLS-derived length agreed well with each other with a high CCC of 0.98 (see Fig. 7C). However, it was not the same case for volume (see Fig. 7D), where we had a lower CCC of 0.78 between the single-scan and multi-scan TLS data. While volume was overestimated by a maximum of 37% for the smallest liana (liana 8) and underestimated by a maximum of 17% (liana 8) for the multi-scan TLS data, volume was overestimated by a maximum of 46% (liana 5) and underestimated by a maximum of 64% (liana 9) when using the single-scan TLS data. These results indicated that multi-scan TLS data were much more reliable for deriving volume estimates than single-scan TLS data for lianas, which had been confirmed for trees by previous studies (Bauwens et al., 2016; Saarinen et al., 2017). As a result, we only compared the AGB from multi-scan TLS data with the AGB from allometric equations for the real lianas.

![Fig. 4. Illustrating the criteria for choosing the model with the lowest difference between the diameter from the point cloud estimated by least square fitting and model estimated by TreeQSM algorithm at different places along the trunk. (A) Least squares circle fit to the liana point cloud slice at 5 m from the ground (z). (B) Comparison of liana stem diameter calculated from the point cloud and TreeQSM at 5 m from the ground for different PatchDiam2Max values with fixed PatchDiam2Min = 0.005 m and lCyl = 3. The error bar indicates the standard deviation of the ten model runs with the same parameter setting.](image-url)
3.3. Comparing TLS and allometric biomass of lianas

We evaluated the distribution of TLS-derived volume with respect to height for all ten real lianas in the Nouragues study site, French Guiana (see Fig. 8). 80% of the estimated volume from TLS was concentrated in the lower 60% of the liana height. When we extrapolated the missing volume in the canopy for the lianas with the stem taper curve as shown in Fig. 6, average missing volume was estimated to be only 5.3% of lianas’s total volume.

We compared the TLS-derived biomass estimates (with extrapolation from stem taper curve) with all the allometric equations listed in Table 3 using ordinary least-squares regression and CCC (see Fig. 10). Though the regression resulted in high $R^2$ values in all the cases, CCC values were consistently low with 0.67 being the highest value. This indicates disagreement between the TLS-derived biomass estimates and estimates from existing allometric models.

Each allometric equation resulted in a wide range of different biomass estimates for liana of the same size, making the choice for a specific equation not straightforward (see Fig. 10). The variation in the biomass was even more prominent for bigger individuals (≥10 cm).

On one hand, the two pantropical allometric equations and allometry from French Guiana and Amazonia overestimated the biomass of larger lianas. But on the other hand, allometric equations from Malaysia and Ghana underestimated the liana biomass (see Fig. 10). For instance, pantropical_all, pantropical_no_ven and Amazonia allometric equation overestimated the total biomass by 133%, 143% and 164% respectively, compared to the TLS-derived biomass estimate. However, allometric model established for a secondary forest in Ghana underestimated the biomass by 81% compared to the TLS-derived estimate.

In addition, the difference between TLS-derived biomass and the pantropical_all allometry-derived biomass increased with increasing liana size (see Fig. 9). All the pantropical and neotropical allometries included both leaf and wood components in their biomass estimates. However, this could only explain 5–10% of the overestimation of biomass and not the observed 133–164% (Castellanos et al., 1992).

4. Discussion

The objective of our study was to test the potential of the emerging TLS technology to estimate liana woody biomass. The main advantage of using TLS to derive liana volume estimates is that TLS data does not require any prior assumptions about liana structure as opposed to conventional allometric relations. This makes TLS data more robust to estimate biomass as lianas are structurally less constrained than trees are. Previous study on liana architecture has shown that many liana species appeared to have a unique architecture of their own, distinct from that of trees (Jacobs, 1976). The length and height and hence the biomass of lianas do not seem to be strongly related to their diameter (see Figs. 12, 11 and Table 2).

This has also been confirmed by studies that have observed rapid rates of growth in length for lianas but slower rates of growth in diameter (Putz, 1990; Condon et al., 1992). It should be noted that the length could potentially still be longer than the ones in Fig. 11, if the occluded parts in the canopy were taken into account. This would explain why the allometric equation that included both diameter and length provided better AGB estimates than the ones with diameter alone (Gehring et al., 2004). But the comparison of TLS-derived biomass with the biomass estimates derived from allometric model
including length had a low CCC of 0.34. One of the possible reasons could be the discrepancy in how the length of a liana is defined. We defined the length of a liana as total length of stem including all the branches. However, it is unclear how the length was defined in the allometric model (Gehring et al., 2004). Nevertheless, given the difficulty of measuring length in the field using conventional methods, TLS facilitates a more reliable way to derive liana biomass by capturing the liana structure in detail below the canopy (where most of the woody biomass is concentrated). We summarize the pros and cons of destructive vs. allometric vs. TLS-derived biomass estimates in the Table 4.

Our TLS-derived liana length and volume (for the multi-scan data) showed good agreement with reference length and volume respectively, for the eleven synthetic lianas. However, there was a bias (15.5% overestimation) in the volume estimated by TLS compared to the true volume for the synthetic lianas. One of the main reasons for the overestimation of TLS-derived length and volume compared to reference length and volume was the small size (diameter) and the material used to make these lianas, which caused them to move between two consecutive scans. The impact of overestimation was much higher in lianas of smaller diameter (<2 cm, which were made mostly of ropes) than in lianas of relatively larger diameter (≥2 cm) (see Fig. 7). Since all the TLS data collected from the real lianas in the field were ≥2 cm, overestimation resulting from slight movement of thinner parts would be negligible. In addition, all TLS instruments are technically limited to resolve smaller elements at increasing distance from the scanner due to their exit diameter (7 mm in this study) and beam divergence (0.35 mrad in this study).

We analyzed the possible sources of error and uncertainty when using TLS to estimate liana stem biomass in the field. One of the main sources of error stemming from applying QSM to TLS data was the volume for parts that are higher up in the canopy, which were difficult to capture with TLS from the ground due to increased occlusion. However, 80% of the estimated volume was concentrated in the lower 60% of the total liana height from the ground (see Fig. 8). Though smaller branches were more numerous, they did not seem to contribute a lot to the total volume of lianas (see Fig. 13A and B). For instance, only 10% of the branches on average were bigger than 80% of the maximum branch diameter. However, these 10% branches contributed to almost 80% of the total estimated volume from all the branches. As a result, smaller branches in the canopy, which were difficult to fully capture from the ground using TLS, contributed negligibly to the total woody biomass of a liana.

Another possible source of uncertainty arises when TLS-derived volume is converted into biomass using wood density. In this study, we used individual liana wood density estimates derived from micro-cores...
Fig. 7. Terrestrial Laser Scanner (TLS)-derived volume and length for the eleven synthetic lianas in Barro Colorado Island (BCI), Panama. (A) Comparison of TLS-derived length and reference length for the eleven synthetic lianas (Table 1). (B) Comparison of TLS-derived volume and reference volume. (C) Plot of the observed differences in TLS-derived length to the reference length per liana for the single- and multi-scan TLS data. (D) Plot of the observed differences in TLS-derived volume to the reference volume per liana for the single- and multi-scan TLS data. In figures A, B, C and D, black color indicates the results from multi-scan TLS data and red color indicates the results from single scan TLS data.

Fig. 8. Terrestrial Laser Scanner (TLS)-derived vertical volume distribution for all ten real lianas from Nouragues, French Guiana.

Fig. 9. Difference in Terrestrial Laser Scanner (TLS)-derived biomass and pantropical_all biomass with respect to increase in liana size for all ten real lianas from Nouragues, French Guiana.
for two main reasons. First, there is no average wood density estimate established for lianas from this region. Unlike for trees, wood density of lianas is understudied with the study of Putz (1990) reporting an average value of 0.4g/cm³ for a secondary forest in Panama and the study of Liana biomass et al. (1983) reporting an average value of 0.48g/cm³ in Venezuela. Total biomass of ten real liana individuals used in this study were underestimated by 17% when average wood density of 0.4g/cm³ was used instead of individual wood density estimates. Second, it was possible to collect micro-core samples from all these lianas considering our small sample size. However, as mentioned in Section 2.1.2, wood density estimates derived from micro-cores should be taken with caution. Nevertheless, it might not be possible to measure wood density of all individual lianas when estimating biomass at plot-level and might introduce some uncertainty. The difference in wood density of lianas in a specific region compared to the pantropical average, could be one of the reasons for the higher biomass estimated by pan-tropical allometric equations compared to the allometric equation established for a secondary forest in Ghana or Malaysia. As a result, choice of the correct value for wood density is crucial for reliable estimation of biomass using TLS (Momo et al., 2018).

Although we did not have direct destructive biomass measurements for lianas, our results from synthetic lianas confirmed the outcome of a number of other studies that proved the potential of TLS to derive more accurate biomass estimates for trees of all sizes (1–180 cm in DBH, diameter at breast height) than the allometry-derived biomass estimates (Kunz et al., 2017; Calders et al., 2015; Gonzalez de Tanago et al., 2018; Momo et al., 2018; Olofsson and Holmgren, 2017). One possible reason for the overestimation of liana biomass by the pantropical allometric equation in Schnitzer et al. (2006), is the lack of destructive biomass data from large lianas (only seven lianas ≥10 cm were used). However, the question if it is possible to establish an allometric model for lianas, even when there are large number of harvested individuals, still remains (see Fig. 12). Schnitzer et al. (2006) mentioned in his study that there is a necessity for more destructively harvested lianas, especially lianas ≥10 cm, to test if liana biomass can be estimated by diameter allometry or not. There are multiple studies showing that lianas are structurally and mechanically weakly constrained to diameter growth (Condon et al., 1992; Putz, 1990; Putz and Mooney, 1991). Castellanos et al. (1992) illustrated how the stem of two different lianas, both in 2–3 cm diameter range, occupied their 3D volume of space differently resulting in a mere 16% increase in biomass for the larger liana as opposed to the 65% increase estimated by pantropical
allometric model. Development of lianas from a sapling to a mature form is highly dynamic depending on the support availability and light microsites in the forest. Lianas can reach the canopy at significantly smaller size classes (> 1.5 cm) in some forests (Kurzel et al., 2006). Their extremely flexible stem and anomalous stem anatomy are found to facilitate their survival in the event of stem damage due to, for example, their host tree fall (Putz and Mooney, 1991).

There are not a lot of studies on liana structure and architecture and the studies that exist have been highly descriptive (Jacobs, 1976; Castellanos et al., 1992). TLS can be used to quantitatively study liana structure and thereby understand the relationship between their structure and allometry. Moreover, TLS can enable the non-destructive sampling of more lianas, including large ones. In addition to length and volume, QSM-based approach offers other exciting output structural parameters like branching order (Fig. 6C), branch angle etc., which can be used to understand the link between plant structure and function, which are yet to be examined for lianas (Disney, 2019).

It is difficult but possible to derive stand-level liana biomass estimates from TLS. However, automatic extraction of lianas from the point cloud of a tropical forest is required to make the plot-level liana biomass estimation feasible as the current manual extraction is a time consuming step in the processing chain. A recent machine learning based algorithm for the semi-automatic extraction of liana woody points from plot-level TLS data holds promise for facilitating plot-level liana stem biomass estimation (Krishna Moorthy et al., 2019). This would enable long-term and reliable monitoring of plots for understanding the dynamics of liana infestation, structure and biomass. This information on liana biomass change relative to the total forest biomass change is important for devising effective management strategies for forest regeneration in liana-abundant areas.

Table 4
Pros and cons of the different methods used for estimating liana biomass.

<table>
<thead>
<tr>
<th>Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
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<tbody>
<tr>
<td>Destructive harvesting</td>
<td>Direct measurement, High accuracy</td>
<td>Difficult and even impossible without severe host tree damage, Upscaling not possible, Labor-intensive, time-consuming and expensive</td>
</tr>
<tr>
<td>Allometry</td>
<td>Non-destructive, Easy to measure diameter in field, Easy to upscale</td>
<td>Indirect size-dependent estimate, High uncertainty (sampling bias), Lianas might not be structurally constrained to establish allometric model</td>
</tr>
<tr>
<td>TLS</td>
<td>Non-destructive, Reliable volume estimates independent of liana size (diameter), Independent of liana structure and architecture</td>
<td>Occlusion in the canopy and registration error due to wind (both hard to quantify), Needs reliable wood density estimates, Upscaling to stand-level is difficult, Expensive and Time-consuming</td>
</tr>
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</table>

Fig. 12. Three lianas from Nouragues, French Guiana, having similar diameters in the range of 4-6 cm exhibiting different structures. This illustrates how complex and variable lianas grow compared to trees.
5. Conclusion

Our study demonstrated the potential of multi-scan TLS data to derive liana-specific structural metrics such as length, volume and indirectly the biomass. As a result, our study facilitates the study of contribution of lianas to carbon cycle in high liana dense forests (e.g., Gigante Peninsula (Van Der Heijden et al., 2016)) and in forests where lianas continue to proliferate (Schnitzer, 2018; Schnitzer and Bongers, 2011; Schnitzer and Carson, 2010). Our study showed that the existing allometric models do not agree with each other or the TLS-derived biomass estimates. All the pantropical and neotropical allometric models overestimated the biomass between 133 to 164% compared to the TLS-derived biomass. Given the variable growth forms of lianas, the presented method will enable us to test if it would be possible to establish allometric equations for lianas by giving us access to larger sample size without destructive harvesting. With recent developments in the field of automatic feature extraction from 3D point cloud data, our study also facilitates plot-level liana biomass estimation from TLS data without the need for allometric equations.

6. Author contributions

S.M.K.M., and H.V. conceived and designed the experiments with inputs from K.C.; S.M.K.M. collected the data; S.M.K.M., P.R. and J.V.B performed the analysis; J.V.B. wrote the section on wood density estimates from micro-cores; S.M.K.M. wrote the paper with critical contributions from all the authors.

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Appendix A. Appendix

A.1. Wood density estimates from micro-cores

The micro-cores of all the ten lianas were oven-dried for 24 h at 103°C and mounted in a custom-made holder (see (De Ridder et al., 2010) for details) with a chemical composition close to that of the wood cell wall (1.4 g/cm³). The samples were scanned with the Environmental Micro-CT Scanner (EMCT) developed by the Radiation Physics Group of the UGent Centre for X-ray Tomography (UGCT, www.ugct.ugent.be) in collaboration with the Ghent University spin-off company formerly known as XRE (TESCAN XRE, part of the TESCAN ORSAY HOLDING a.s.). This scanner has a rotating X-ray tube and detector, and thus the sample remains static. More details on the scan system and the acquisition software can be found respectively in Dierick et al. (2014) and Dierick et al. (2010). Scans were performed at 100 kV, using a hardware filter of 0.5 mm for reducing beam hardening and with an exposure time of 70 ms and 6 averages per projection for a total of 2000 projections. The duration of a scan was 14 min, and a voxel pitch of approximately 26.8 µm was obtained after reconstruction using the Octopus Reconstruction software package (Vlassenbroeck et al., 2007). Samples were analysed using the procedure described in De Ridder et al. (2010) for conversion of attenuation coefficients to density values by using the software packages reported in Van den Bulcke et al. (2014) and De Mil et al. (2016).
A.2. TLS scans of field lianas

Fig 14.

Fig. 14. Illustration of TLS data of all the ten lianas and their host canopies from Nouragues, French Guiana (see Table 2). We indicate the manually extracted liana stems from the TLS data in black color and the rest of the point cloud belonging to leaves, trees, etc. in gray color. The height above the ground of the extracted liana stems and their corresponding host canopies are also indicated in the figure.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2019.117751.

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