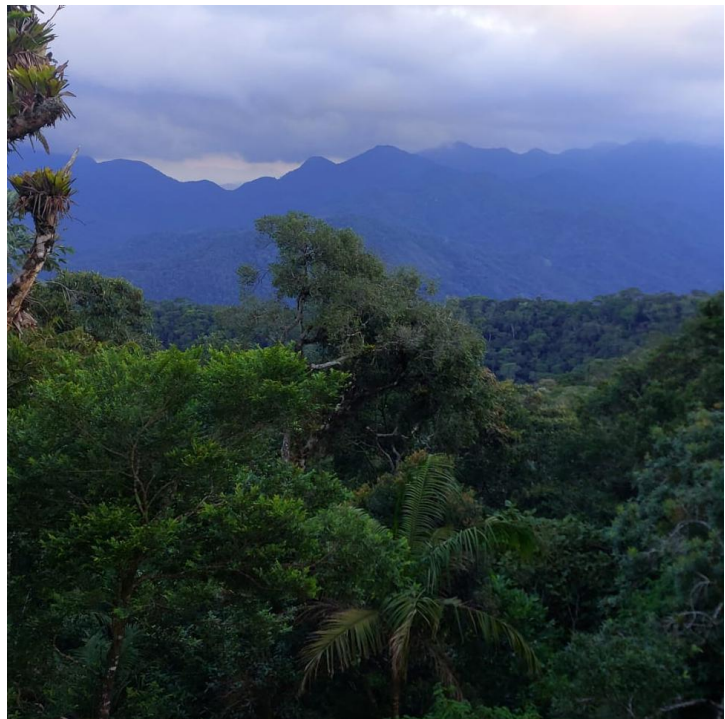




UNIVERSITY OF  
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ENVIRONMENTAL SCIENCES

# DO STANDARD TROPICAL FOREST MONITORING PROTOCOLS BIAS HEIGHT– DIAMETER ALLOMETRIES?



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*Cover photo taken by Daniel Lindahl*

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## Abstract (Svenska)

Vanligen använda protokoll för tropisk skogövervakning utesluter träd med särskilda egenskaper vid mätning av trädhöjd. Här uppskattade vi förekomsten av uteslutande egenskaper (Brutet, Fallet, Lutande och Ruttet) och deras effekt på höjduppskattningar för träd i en 1-hektars provyta i den bergiga Atlantiska skogen. Vi uppmätte förekomsten av uteslutande egenskaper för provytans 801 träd och anpassade en allometrisk höjd–diameter vid brösthöjd (dvs., vid 1,30 m; DBH) (H:D) -modell, baserad på en delmängd av 81 träd, för att fastställa om dessa egenskaper hade en inverkan på det allometriska H:D förhållandet. Av dessa 81 träd saknade 40 uteslutande egenskaper (dvs. de var "standardträd" enligt protokollet), medan 41 uppvisade minst en sådan egenskap (dvs. "ej-standardträd"). Vi fann att 252 av de 801 träden (31,5 %) uppvisade uteslutande egenskaper. Den mest framträdande egenskapen var Lutande (28,3 % av de 801 träden), medan övriga egenskaper förekom relativt sällan (under 2,5 % per egenskap). För både standard- och ej-standardträd ökade trädhöjden systematiskt med ökande DBH. Samtidigt skilde H:D-förhållandet signifikant mellan de två delmängderna: Vid en given DBH var höjden hos ej-standardträd signifikant lägre än höjden hos standardträd. Givet den höga förekomsten av uteslutande egenskaper och den signifikanta skillnaden i H:D-förhållandet, indikerar våra resultat att protokolls selektion av träd med särskild standard för höjdmätning leder till en signifikant överskattning av trädhöjd och därmed även uppskattningar av biomassa och kolförråd.

Nyckelord: fältmättningsprotokoll, trädsallometri, trädhöjds-mätning, övervakning av tropisk skog

## Abstract (English)

The widely used protocols for monitoring tropical forests exclude trees with certain characteristics when measuring tree heights. Here, we estimated the prevalence of exclusion characteristics (Broken, Fallen, Leaning and Rotten) and the effect on tree height estimates for trees in a 1-ha plot in the mountainous Atlantic Forest. We recorded the prevalence of exclusion characteristics from the 801 trees in the plot and then fitted an allometric Height–Diameter at Breast Height (i.e., at 1.30 m; DBH) (H:D) model from a subset of 81 trees to establish if the exclusion characteristics had an impact on the allometric H:D relationship. Of these 81 trees, 40 had no exclusion characteristics (i.e., they were the “standard” trees according to the protocol), and 41 presented at least one of the exclusion characteristics (i.e., “not standard” trees). We found that the exclusion characteristics were exhibited in 252 (31.5%) of the 801 trees. Leaning was the predominant characteristic (28.3% of the 801 trees), while the others were recorded relatively rarely (below 2.5% per characteristic). For both the standard and non-standard trees, tree height increases systematically with increasing DBH. However, the H:D relationship was significantly different between the two sets of trees: For given DBH, the height of non-standard trees was significantly lower than the height of standard trees. Given the high prevalence of exclusion characteristics, and that there is a significant difference in the H:D relationship, our results indicate that protocols selecting trees of a certain standard for height measurements significantly overestimate the tree height and thereby estimates of biomass and carbon stocks.

Keywords: field measurement protocols, tree allometry, tree height measurement, tropical forest monitoring

# 1. Introduction

## 1.1. The carbon cycle and aboveground biomass

As climate change remains a constant global challenge, understanding the carbon cycle is paramount. The carbon cycle is a loop in which carbon alternates between being fixed (e.g. in living organisms) and being atmospheric (e.g. as carbon dioxide) (Prentice et al., 2001). High levels of carbon dioxide in the atmosphere have multiple detrimental effects, such as acidification of oceans and increased global temperature (Prentice et al., 2001). Since the industrial revolution, the atmospheric concentration of carbon dioxide has increased to a level that most likely has been unprecedented for the past 20 million years (National Oceanic and Atmospheric Administration [NOAA], 2026; Prentice et al., 2001). While there are global goals being set about reaching a net-zero of greenhouse gas emissions, there has been great losses of fixed carbon primarily due to changes in land use (Pan et al., 2024). The uptake of carbon dioxide by terrestrial ecosystems has a vital role in regulating atmospheric concentrations. When estimating fixed carbon, it is done as a snapshot in time, these estimations are called carbon stocks (Intergovernmental Panel on Climate Change [IPCC], 2006; NOAA, n.d.). Biomass is a common parameter used when estimating carbon stocks (IPCC, 2006), as approximately 50% of biomass is in general assumed to be carbon (Basuki et al., 2009). Different definitions of biomass are used depending on context, but in general it refers to the dry mass of living organic matter (Herold et al., 2019). Aboveground biomass (AGB) is the biomass above soil (Herold et al., 2019), and the majority of the world's AGB is found in tropical forests (Pan et al., 2013, 2024).

## 1.2. Allometry and tropical forests

A widely accepted method of estimating AGB is to use allometric models (Feldpausch et al., 2011; IPCC, 2006; Picard et al., 2012). Allometry refers to the proportional relationship between attributes in an organism (Picard et al., 2012). For example, how high a tree is in relation to its diameter, and how it changes to a certain power. Based on these relationships, biomass is estimated as a function of diameter, height and wood specific gravity (essentially wood density) (Cushman et al., 2021; Zuleta et al., 2023). Furthermore, the height is estimated from the diameter, by generalizing the relationship from a sample (Picard et al., 2012; Réjou-Méchain et al., 2017). While allometric measurements aim to provide generalized expectations of tree form and size (Arellano et al., 2021), tropical forests are known to be biodiverse and have an extreme variation in tree form and size, which makes it cumbersome to generalize (Feldpausch et al., 2011; Pan et al., 2013; Réjou-Méchain et al., 2017).

## 1.3. Common practice in tropical forest monitoring

A widely used protocol for monitoring biomass and dynamics in tropical forests is the RAINFOR (The Amazon Forest Inventory Network) protocol (Phillips et al., 2021; RAINFOR Network, 2026). This protocol includes instructions on how to set up monitoring plots, measure trees in a consistent manner, and more (Phillips et al., 2021). Measuring a tree in accordance includes tasks such as recording the diameter at breast height (DBH, the diameter at 1.3 m above ground), the height, and codes for characteristics of the tree. For example, a tree that is alive, but rotten and leaning 10% or more, is recorded with the codes G and C. The protocol states the following about height measurement, regarding the allometric relationship Height–DBH (H:D):

“The aim is to characterise the ‘ideal’ height/diameter curve as determined by climatic and edaphic conditions and not confused by the influence of damaged trees” (Phillips et al., 2021).

Followed by the instruction that trees with the following characteristics must be excluded from height measurements: Broken (without a new proper stem growing), Leaning (more than 10%), Rotten (or presence of bracket fungus), Forked below 5m, Fallen or Resprouted.

However, trees are not perfect, they vary in shape, size and allometry depending on numerous factors. Generalizing something with great variation is done with difficulty. Therefore, there might be systematic errors in estimating forest biomass.

## 2. Aims

Estimating the allometric H:D relationship of tropical forests with commonly used protocols means excluding trees with certain characteristics (Broken, Fallen, Leaning and Rotten) when measuring heights. This study aims to see how common these characteristics are. As well as test whether there is a difference in the allometric H:D relationship between trees who are exhibiting these characteristics, and trees who are not.

- Question 1: What is the prevalence of these exclusion characteristics (Broken, Fallen, Leaning and Rotten) among trees in the study area?
- Question 2: Do trees with non-standard physical characteristics differ in their H:D relationship from Standard trees?

## 3. Materials and methods

### 3.1 Data collection

The data for this study were collected over the course of three months (April–July 2026), to which I contributed as part of the field team.

#### 3.1.1. Study area

The study was conducted in a mountainous region of the Atlantic Forest in Rio de Janeiro State, Brazil. The study area was a 1 ha plot, established following the guidelines of the RAINFOR Field Manual for Plot Establishment and Remeasurement (Phillips et al., 2021), see the digital version of the plot in Figure 1a. The plot sits in a steep terrain, with elevation ranging from 1429 m a.s.l. to 1467 m a.s.l. The RAINFOR protocol is mainly used for flat areas. To account for the sloped terrain, the plot was adjusted to correspond to 1 ha on flat surface. To do this, trigonometry, a measuring tape, a compass, and a clinometer (a tool to measure angles with) were used. The plot and its corners delimiting the quadrats were marked with PVC-pipes and plastic string.

#### 3.1.2. Measuring DBH

All trees and lianas in each quadrat were inspected. If deemed alive at 1.30 m, the DBH of the individual was measured. If larger than, or equal to, 10 cm, the individual was recorded, tagged and painted (Figure 1b & 1c). The point of measurement (POM) of all individuals was recorded, mainly located at 1.30 m (the height defined for DBH). However, when stem irregularities occurred at 1.30 m, the diameter was measured either at 1.28 m, or above 1.30 m, at a point where the diameter was representative of the stem. Recorded trees were inspected for physical characteristics, which were documented using codes defined in the RAINFOR protocol. (The complete list of codes is provided in Appendix 1)

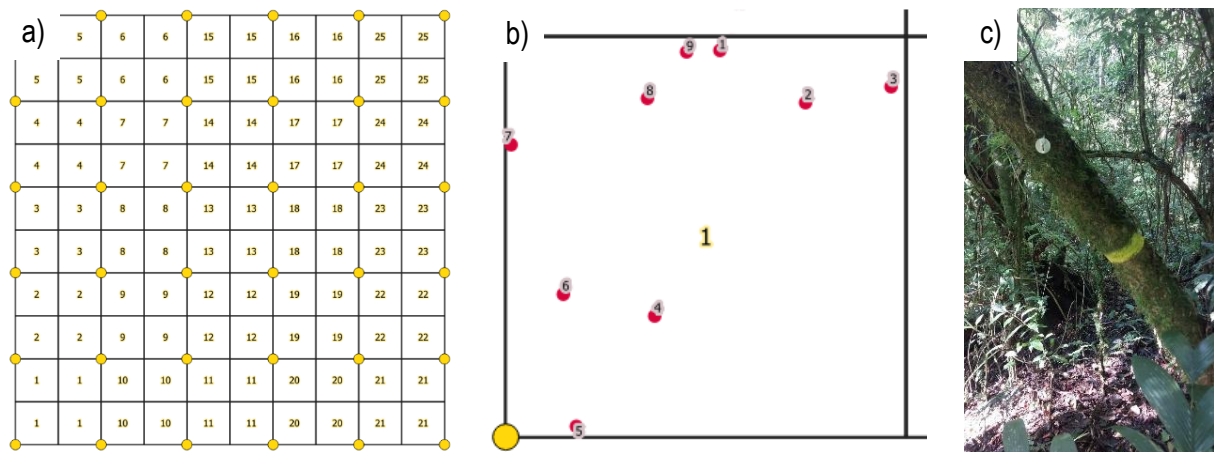


Figure 1: Recording of data in the field. a) A QGIS project was used with a tablet for recording. The grid represents a 1 ha plot. The yellow dots mark the corners of 20 x 20 m subplots, made up by four 10 x 10 m quadrats. The subplots are identified with a number, here marked in its 4 quadrats. b) Trees and lianas were recorded in clockwise order, topologically represented in the tablet. As identification a number following a consecutive order was given. c) The recorded individuals received an aluminium tag with its unique identification-number, attached with hammer and nail. The individuals were painted yellow at their respective point of measurement (POM). The trees also had characteristic codes recorded, this tree received code C, for leaning more than 10%.

After excluding lianas, tree ferns, palms and erroneous entries, the dataset consisted of 801 trees representing multiple species.

### 3.1.3. Height measurements

According to the RAINFOR protocol, a height measurement sample should consist of at least 10 randomized trees from 4 DBH-classes (different ranges of DBH-sizes), to ensure enough variation to fit a reliable model. The DBH classes are trees with a DBH of 10-20 cm, 20-30 cm, 30-50 cm, and larger than 50 cm. Due to a lack of trees above 50 cm in this forest, the third class was defined as 30-40 cm, and the fourth was defined as larger than 40 cm. A total of 109 trees were measured for height. The sample comprised 40 trees that were up to protocol standard (10 trees from each DBH class), 41 trees that were not up to protocol standard (10 trees from each DBH class, with one additional tree in the 20–30 cm DBH class), and 28 randomly selected trees (7 trees from each DBH class), which were included as an unbiased reference sample.

The height measurement of a tree was performed by a team of two. One observer positioned themselves at an appropriate distance and recorded the angles of the highest and the lowest point of the tree using a clinometer. In accordance with protocol recommendations, to minimize handheld error, angles below 45 degrees were recorded whenever possible. The second observer measured the distance along the line of sight between the first observer and the lowest point of the tree. Using these measurements, tree height was calculated trigonometrically (Figure 2).

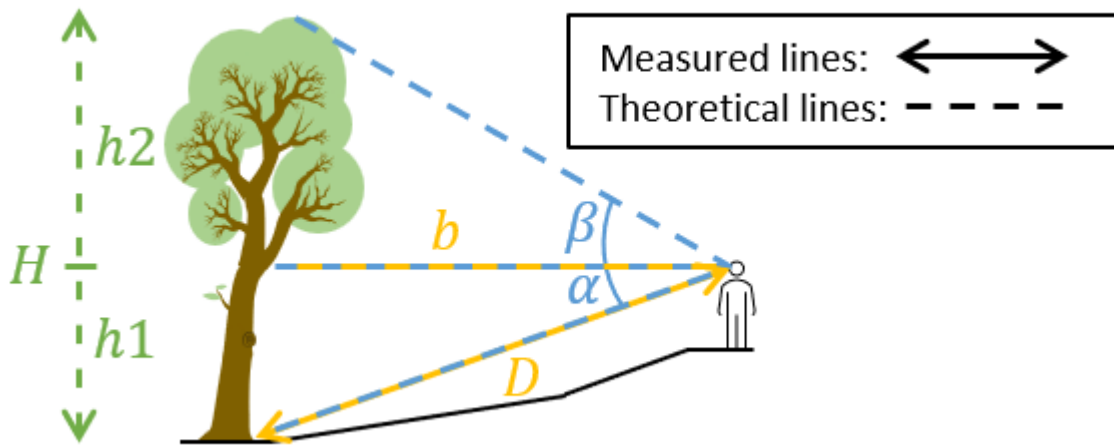


Figure 2: Estimation of tree height with trigonometry.  $\alpha$  is a negative angle from what is 0 degrees at the persons eyes, to the bottom of the tree.  $D$  is the distance from the point where  $\alpha$  was taken, to the bottom of the tree. This gives a right triangle where  $h1$  is the opposing side to  $\alpha$ , and  $D$  is the hypotenuse. Enabling the equation  $h1 = \sin(\alpha) \times D$ . The side  $b$  can be calculated through  $b = \frac{h1}{\tan(\alpha)}$ .  $\beta$  is a positive angle to the highest point of the tree. Knowing  $b$  and  $\beta$ , allows  $h2 = \tan(\beta) \times b$ . Now knowing both  $h1$  and  $h2$  allows  $H = h1 + h2$ , where  $H$  is the height of the tree.

When measuring the stem-length of leaning trees, the same procedure as in Figure 2 was conducted, resulting in a height corresponding to if the tree was growing straight. Additionally, to account for the leaning stem Pythagoras theorem was used, explained in Figure 3. The stem-length of leaning trees is hereafter referred to as Height.

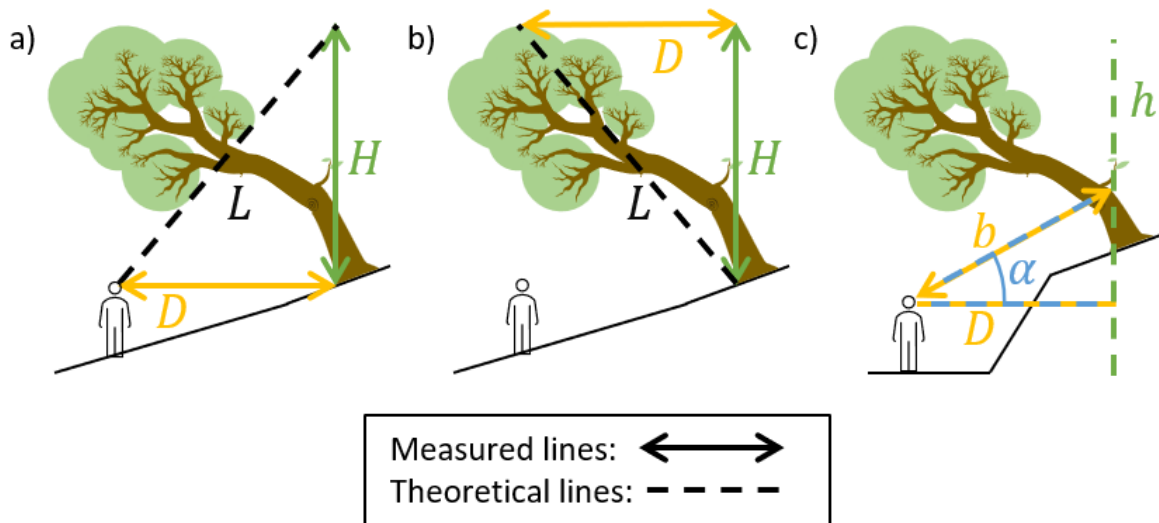


Figure 3: Estimation of tree height (or stem length) in leaning trees with trigonometry. a)  $H$  is the height of the tree if it was growing straight (acquired as instructed in Figure 2).  $D$  is the distance from beneath the highest point of the tree to the stem of the supposed straight tree, measured in a 0-degree angle to create a theoretical right triangle, where  $L$  is the hypotenuse. b)  $L$  represents the length of the leaning stem, acquired through Pythagoras theorem  $L = \sqrt{H^2 + D^2}$ . Easier visualised with the triangle mirrored. c) If the highest point of the tree is above a place where getting the distance on a 0-degree angle to the supposed straight tree is impossible, another theoretical right triangle can be created. By getting an angle  $\alpha$  and a distance  $b$ , to a point along the line of the supposed straight tree ( $h$ ), a new theoretical right triangle is created, where  $D$  is the same  $D$  as shown in a) and b).  $D$  is acquired through  $D = \cos(\alpha) \times b$ .

## 3.2. Data analysis

### 3.2.1. Diameter correction

Of the 801 recorded trees, 254 trees (31.7%) had a POM different from the standard height of 1.30 m and therefore required DBH correction using a taper model (Cushman et al., 2014). For the trees with non-standard POM the following model developed by Cushman et al. (2021) was used:

$$b = 0.156 - 0.023 * \ln(DAB) - 0.021 * \ln(POM) + Site$$

*DAB* refers to the diameter measured. *POM* is the actual height at which the diameter was measured at. *Site* (site random effect) is not to be used when applying the model to new sites, as in this case. The correction factors (*b*) were used to calculate the equivalent diameter at 1.30 m for the individual trees with the following equation (Cushman et al., 2021) (where *EDBH* is estimated DBH):

$$DAB = EDBH * e^{-b(POM-1.30)}$$

The corrected DBH values were generally similar to the original measurements, with larger adjustments occurring primarily for trees measured from the standard POM (Figure 4). Only corrected DBH values were used in subsequent analyses.

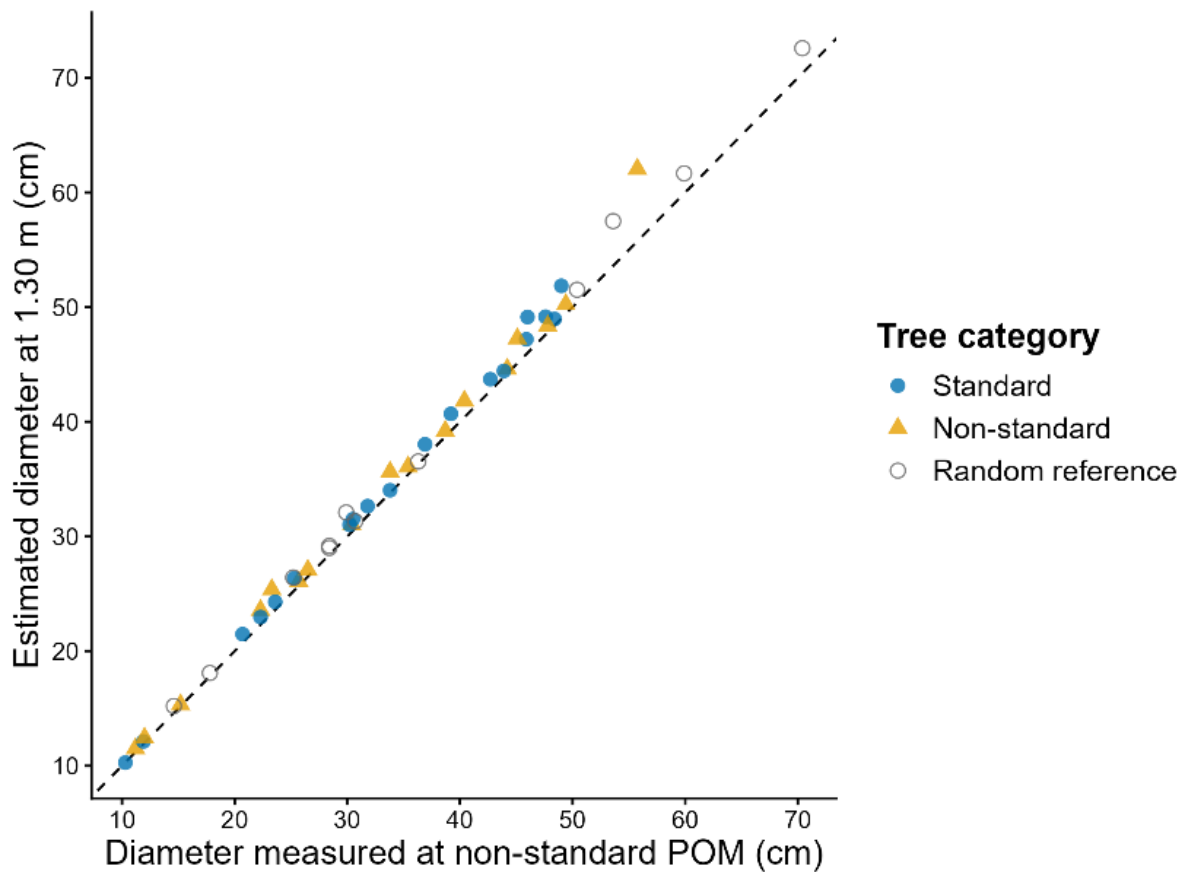


Figure 4: Comparison between the measured diameter at the non-standard POM and the corresponding diameter re-estimated to breast height (1.30 m) using a taper model. Showing the 48 trees with non-standard POM, out of the 109 trees of the height sample. Colours indicate tree category. The dashed 1:1 line represents no correction: points above the line indicate trees whose estimated DBH exceeded the measured diameter, while points below the line indicate the opposite.

### 3.2.2. Physical characteristics of trees in the study area (Question 1)

The frequency of the four characteristics excluded by RAINFOR (Broken, Fallen, Leaning and Rotten) was calculated across all 801 recorded trees in the plot. Trees without any exclusion characteristics were classified as Standard, whereas trees exhibiting one or more exclusion characteristics were classified as Non-standard.

### 3.2.3. Height–DBH allometries (Question 2)

To answer question 2, the dataset consisted of the 40 Standard and the 41 Non-standard trees for which height measurements were recorded. The H:D relationship was modelled using the commonly applied power function:  $Height = b \times DBH^a$  (Picard et al., 2012). In line with common practice for allometric modelling, the function was log-transformed using the natural logarithm. This stabilises variance and improves the normality of the residuals (Basuki et al., 2009; Picard et al., 2012). Transforming the function into a linear form, which the log-transformation does, is of interest due to the fact that its coefficients will be estimated using closed-form expressions, allowing the use of Ordinary Least Squares (Picard et al., 2012). The transformation yields the equation:  $\ln(Height) = \ln(b) + a \times \ln(DBH)$ .

To test whether Standard and Non-standard trees differed in their H:D relationship, a linear regression including an interaction between centered  $\ln(DBH_c)$  and tree category was fitted:

$$\ln(Height) = \beta_0 + \beta_1 \ln(DBH_c) + \beta_2 Category + \beta_3 \ln(DBH_c) \times Category + \varepsilon$$

The predictor  $\ln(DBH_c)$  was centered at the geometric mean DBH of the complete dataset. Centering allowed the model intercept to represent the expected height of a tree with the average DBH in the study area rather than an unrealistic tree with  $DBH = 1$  cm, thereby making comparisons between categories biologically meaningful.

The fitted model allowed three biologically relevant hypotheses to be evaluated. First, the coefficient for centered  $\ln(DBH_c)$  ( $\beta_1$ ) estimated the allometric scaling exponent for Standard trees. Second, the category coefficient  $\beta_2$  tested whether Standard and Non-standard trees differed in expected height at the mean DBH, corresponding to a vertical shift between the two allometric relationships. Finally, the interaction coefficient ( $\beta_3$ ) tested whether the allometric scaling exponent differed between categories, indicating whether height increased with DBH at different rates in Standard and Non-standard trees. A non-significant interaction would indicate that both categories follow parallel H:D relationships that differ only in intercept, whereas a significant interaction would suggest different allometric scaling between the two groups.

Model terms were evaluated using Type II analysis of variance (ANOVA), which tests the contribution of each predictor while accounting for the presence of the remaining terms in the model (Fox & Weisberg, 2019). Statistical significance was assessed at  $\alpha = 0.05$ . Model residual diagnostics were used to assess normality and homoscedasticity.

### 3.2.4. Model predictions

To visualize differences in the H:D relationship between Standard and Non-standard trees, predicted tree heights were generated from the fitted regression model across a range of DBH values. Because the model was fitted on the natural logarithm of height, predictions were initially obtained on the log scale and subsequently back-transformed to meters.

Back-transformation of log-transformed regression models systematically underestimates the expected response because the expectation of the exponentiated residuals is greater than one (Basuki et al., 2009; Duan, 1983; Picard et al., 2012). To account for this retransformation bias, Duan's non-parametric smearing estimator was applied. The smearing factor was calculated as the mean of the exponentiated model residuals:

$$SF = \frac{1}{n} \sum_{i=1}^n e^{\hat{\epsilon}_i}$$

And the predicted heights were obtained as:

$$\hat{H} = SF \times e^{\ln(\hat{H})}$$

Predictions were restricted to the range of DBH values shared by both Standard and Non-standard trees, defined by the largest observed minimum DBH and the smallest observed maximum DBH among the two categories. Restricting predictions to the common observed range avoided extrapolation beyond the available data and ensured that comparisons between categories were made only where empirical observations existed.

To visualize the uncertainty in the fitted relationship, 95% confidence intervals for the mean predicted height were calculated from the fitted regression model and back-transformed using the same smearing correction.

## 4. Results

### 4.1. Physical characteristics of trees in the study area (Question 1)

The 801 measured DBHs ranged from 10.00 cm (the inclusion threshold) to 74.30 cm, corresponding to an estimated maximum DBH of 78.80 cm after correcting for measurements higher than 1.30 m. During the inventory, each tree was assigned the RAINFOR condition codes. In total, 252 trees (31.5%) exhibited at least one exclusion characteristic. Leaning was by far the most common condition, whereas Broken, Fallen and Rotten trees were comparatively uncommon (Figure 5).

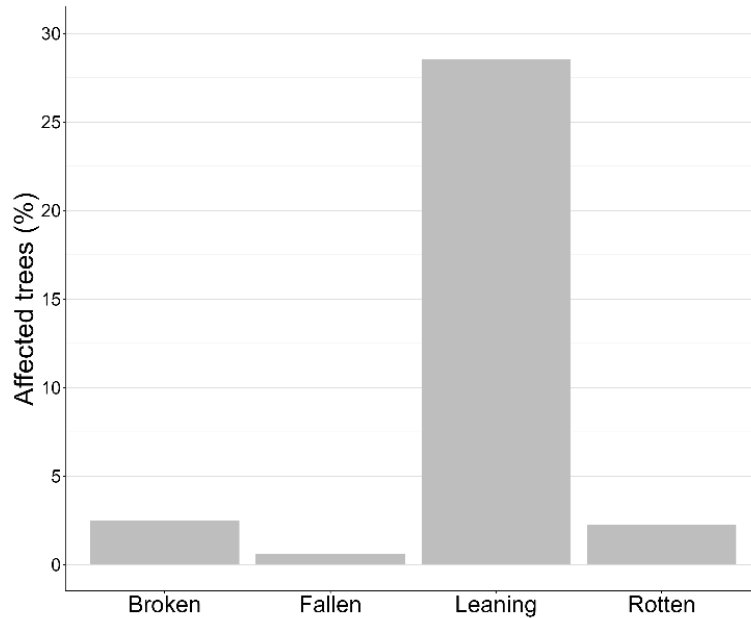


Figure 5: Proportion of the 801 recorded trees exhibiting characteristics that according to the RAINFOR protocol, make a tree ineligible for height measurements (Broken, Fallen, Leaning and Rotten). In total, 252 trees (31.5%) exhibited one or more exclusion characteristics. Some trees had multiple characteristics: therefore, the percentages shown for individual conditions do not sum to the total proportion of excluded trees. Leaning was the predominant exclusion characteristic.

## 4.2. Height–DBH allometries (Question 2)

The fitted allometric model showed a significant positive relationship between DBH and tree height for Standard trees ( $\beta = 0.495$ ,  $SE = 0.056$ ,  $p < 0.001$ , 95% CI = 0.385–0.606), indicating that tree height increased systematically with increasing DBH. The interaction between DBH and tree category was negative ( $\beta = -0.167$ ,  $SE = 0.082$ ,  $p = 0.044$ ), demonstrating that the H:D relationship differed between Standard and Non-standard trees. Specifically, the estimated allometric scaling exponent for Non-standard trees was 0.328 ( $SE = 0.060$ , 95% CI = 0.209–0.447), indicating that height increased more slowly with DBH than for Standard trees.

Overall, the model explained approximately 60% of the variation in log-transformed tree-height (adjusted  $R^2$ ). Model diagnostics indicated no substantial violations of the assumptions of linear regression. Residuals were approximately normally distributed (Shapiro–Wilk,  $p = 0.739$ ), no clear evidence of heteroscedasticity was detected (Breusch–Pagan,  $p = 0.052$ ), and variance inflation factors indicated no problematic collinearity.

Type II ANOVA (Table 1) confirmed that both DBH and tree category significantly contributed to explaining variation in tree height. DBH explained the largest proportion of the variation ( $SS = 3.447$ ,  $p < 0.001$ ), while tree category also had a significant effect ( $SS = 0.267$ ,  $p = 0.005$ ). The significant interaction between DBH and tree category ( $SS = 0.137$ ,  $p = 0.044$ ) supports the conclusion that the H:D relationship differs between Standard and Non-standard trees.

Table 1: Type II ANOVA for the H:D model, including DBH, tree category, and their interaction as predictors.

|                                                       | Sum of Squares | Degrees of Freedom | F value    | Pr(>F)       |
|-------------------------------------------------------|----------------|--------------------|------------|--------------|
| Corrected DBH                                         | 3.4473877      | 1                  | 105.498851 | 4.402938e-16 |
| Tree category<br>(Standard or Non-<br>standard trees) | 0.2671334      | 1                  | 8.174964   | 0.005462445  |
| DBH-by-category<br>interaction                        | 0.1365600      | 1                  | 4.179086   | 0.04434445   |
| Residuals                                             | 2.5161303      | 77                 |            |              |

A smearing factor of 1.015 was estimated and applied when back-transforming predictions from the log scale, corresponding to a correction of approximately 1.5% for retransformation bias. Predicted H:D relationships are shown in figure 6. Across the observed DBH range, Standard trees were consistently predicted to be taller than Non-standard trees of equivalent diameter, with the difference becoming more pronounced among larger trees.

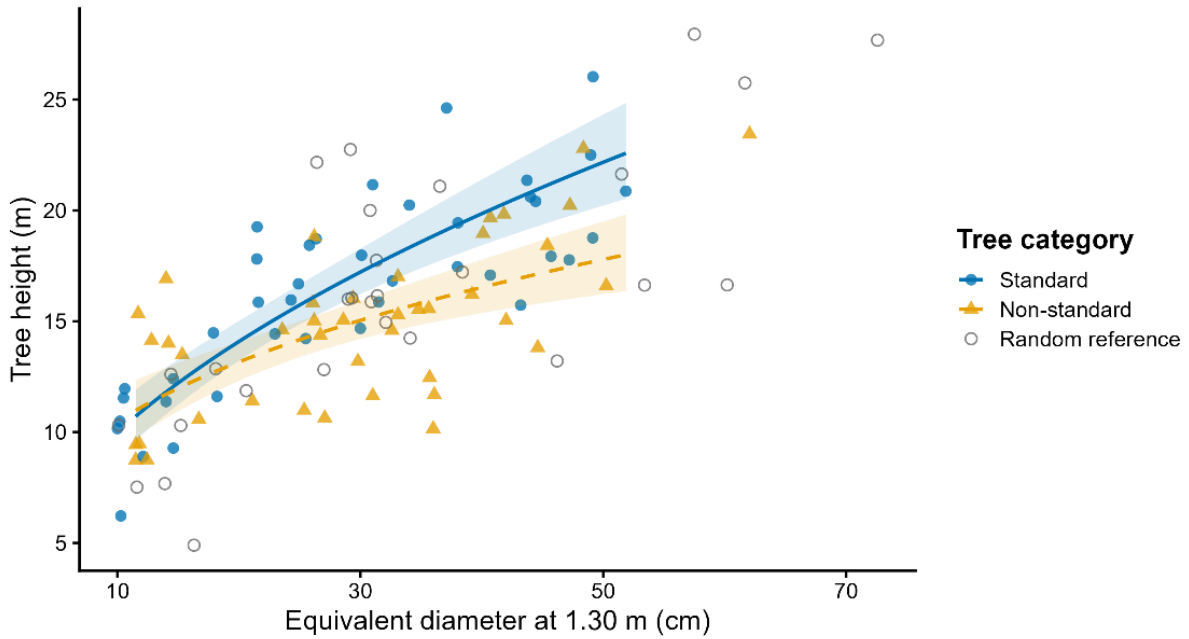


Figure 6: Fitted H:D relationships for Standard (blue) and Non-standard (orange) trees. Solid and dashed lines represent model predictions, with shaded ribbons indicating 95% confidence intervals. Predictions were back-transformed to the original scale using Duan’s smearing estimator. Grey circles represent the 28 randomly selected reference trees, which were not included in model fitting.

## 5. Discussion

### 5.1. A high prevalence of exclusion characteristics in tropical forests

We found that 31.5% of our recorded trees exhibit exclusion characteristics. Leaning was heavily predominant (28.3%). The definition of a leaning tree according to the RAINFOR protocol:

“Alive, leaning by  $\geq 10\%$ . The leaning code cannot be used with the fallen code 'd'.” (Phillips et al., 2021)

A vague description, which renders inconsistency in a forest where stems are not solely straight (Figure 7). Zimmerman et al. (1994) defines leaning trees as those that lean more than  $45^\circ$  from the vertical. Measuring the angle of the lean, from the tree base to the POM (Arellano et al., 2021), was done across six lowland tropical forests, with results showing about 30% of trees to be leaning  $10^\circ$  or more (Zuleta et al., 2022), similar to our results.

A substantial part of trees in tropical forests tend to lean. Perhaps common practice should start taking this into consideration.



Figure 7: A tree that is straight for 3–5 m, then starts leaning heavily for 2–3 m. Should this be considered leaning or not? (Image altered to demonstrate a point)

## 5.2. The overestimation of tree height

We found the H:D relationships of Standard and Non-standard trees to have a significant difference. For both groups tree height increased systematically with increasing DBH, with a slower increase for Non-standard trees.

$$\text{Standard: Height} = e^b \times \text{DBH}^{0.495} \times SF$$

$$\text{Non-standard: Height} = e^b \times \text{DBH}^{0.328} \times SF$$

This indicates that the presence of exclusion characteristics, does in fact impact the allometric H:D relationship.

Assuming a constant H:D relationship could mean systematic errors (Feldpausch et al. 2011), which could result in overestimation of tree height (Carle et al., 2026). Following protocol here, within our study, means incorrectly applying the Standard equation to 31.5% of the trees, leading to an overestimation of height. For montane tropical forests in the Democratic Republic of Congo it was suggested that there is a need for multiple H:D allometric equations within a single forest type (Imani et al., 2017). In relation to our study, the only additional effort beyond common practice was to measure tree height for two subsets of trees, rather than one.

## 5.3. The effect of overestimated tree height

Biomass and carbon stocks are used as a metrics when monitoring progress towards internationally agreed sustainability and climate objectives (Carle et al., 2026; Herold et al., 2019; United Nations Framework Convention on Climate Change [UNFCCC], 2015; Zuleta et al., 2023). With tree height being overestimated for such a large proportion of trees as our results show, biomass and carbon stocks are likely to be inaccurate.

Tropical forests are difficult to generalize (Arellano et al., 2019, 2021; Feldpausch et al., 2011; Pan et al., 2013), and estimating AGB correctly is often deemed difficult (Feldpausch et al., 2011; Réjou-Méchain et al., 2017). However, these estimations are used in important contexts, and the more precise they are, the better.

## 5.4. Current and future directions

There are methods and protocols being designed and tested, with the intention to achieve a higher precision in estimations of H, DBH, biomass and more. Zuleta et al. (2023) describes how in tropical forests physical damage to living trees, such as branch fall, is an important component in biomass loss. Annual mortality and damage surveys (AMS) is a field protocol designed to quantify physical damage to trees (Arellano et al., 2021). A measured diameter often means a healthy tree (Clark et al., 2001), AMS is a step in the direction away from this problem.

Remote sensing techniques, such as Terrestrial Laser Scanning (TLS), have shown promise in generating point clouds from where tree height and DBH can be measured (Beyene, 2020). However, so far these methods are relying on complimentary manual field measurements, and struggle with occlusion due to the structural density of tropical forests (Beyene, 2020; Carle et al., 2026; Hepner et al., 2026). This study is a side-project of a larger research effort led by Luisa F. Gómez-Correa and Dr. Daniel Zuleta at the University of Gothenburg. The research is focused on using TLS to study biomass, carbon stocks and tree architecture in mountainous tropical forests.

## 5.5. Potential errors and limitations of this study

Measurements (DBH, POM, lengths, angles, etc.) and recordings of characteristics are potential sources of error, due to handheld errors and parts of the protocol inviting subjectivity. At times measuring heights was done with difficulty, i.e. finding a position with a sufficient view of the two angles needed (Figure 8). Possibly leading to the measurement of an incorrect highest point. Occasionally the measuring tape was stretched around, over or under objects, adding to the distance measured. If our instincts did not agree with the numbers, trees were remeasured from a different position.



Figure 8: An example of how dense and steep the study area could be at times, making it difficult to accurately measure the height of trees.

This study is looking at trees being excluded for height measurement by the RAINFOR protocol. Here there are 4 characteristics being investigated, the protocol additionally excludes

trees that are forked below 5 m, and trees that are resprouting. No data was recorded of these aspects for the 801 trees, hence this not being part of this study.

With more time, a prediction of the height of the 801 measured trees would be interesting. To compare the results of using one equation across 801 trees and using two equations across 801 trees, in order to quantify the difference in volume (and/or biomass) estimations within 1 ha.

## 5.6. Conclusion

In this study, we quantified the prevalence of exclusion characteristics (Broken, Fallen, Leaning and Rotten) that render trees ineligible for height measurement under the widely used RAINFOR protocol. Across the 801 trees recorded, 31.5% exhibited at least one exclusion characteristic, with leaning being predominant (28.3%).

We also evaluated if there was a difference in the allometric Height–DBH relationship between standard (eligible) and non-standard (ineligible) trees. Height increased systematically with DBH for both subsets of trees. However, a significant difference was shown ( $\beta = -0.167$ ,  $SE = 0.082$ ,  $p = 0.044$ ). The height-increase with DBH of non-standard trees was slower than for standard trees, meaning that for a given DBH, non-standard trees were consistently shorter.

In conclusion, a substantial proportion of trees in tropical forests, are being systematically overestimated by standard protocols that are cherry-picking trees for height measurement. This introduces a structural bias, that most likely affects estimations of biomass and carbon stocks.

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# Appendices

## Appendix 1:

Full list of codes for trees according to RAINFOR (Phillips et al., 2021).

a= Alive normal, should be used by itself unless a tree is a recruit (n) or multi-stemmed (h) individual.

b= Alive, broken stem/top & resprouting, or at least live phloem/xylem. Write in the comments column at what height the stem is broken.

c= Alive, leaning by  $\geq 10\%$ . The leaning code cannot be used with the fallen code 'd'.

d= Alive, fallen (e.g. on ground)

e= Alive, tree fluted or/fenestrated

f= Alive, hollow

g= Alive, rotten and or presence of bracket fungus

h= Multiple stemmed individual. Each stem  $>99\text{mm}$  gets a number. Always use with another code e.g. if a tree is broken and with multiple stems use 'bh'.

i= Alive, no leaves, few leaves

j= Alive, burnt

k= Alive, snapped  $< 1.3\text{m}$  (therefore the diameter at 1.3m is 0mm)

l= Alive, has liana  $\geq 10\text{cm}$  diameter on stem or in canopy

m= Alive, covered by lianas. Use where canopy is at least 50% covered by lianas, even if no individual liana reaches 10cm diameter.

n= Alive, new recruit. Always use with another code- e.g. if a stem is normal and new then use the code 'an', if a stem is broken and a new recruit the code is 'bn'.

o= Alive, lightning damage

p= Alive, cut

q= Alive, peeling bark (bark loose/flaking)

s= Alive, has a strangler

w= Alive, has wound and/or cambium exposed

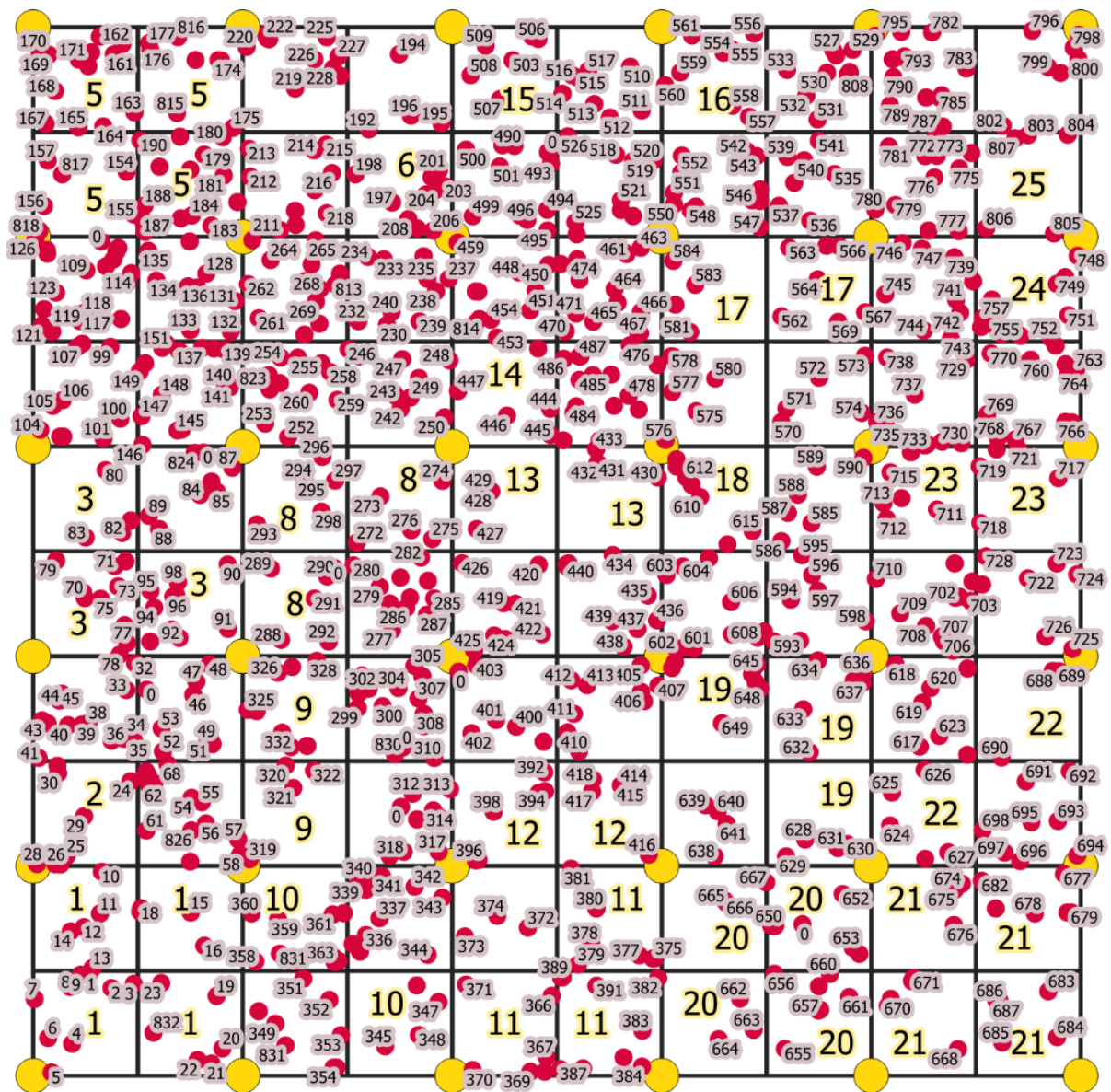
x= Alive, elephant damage

y= Alive, termite damage

z= Alive, declining productivity (nearing death)

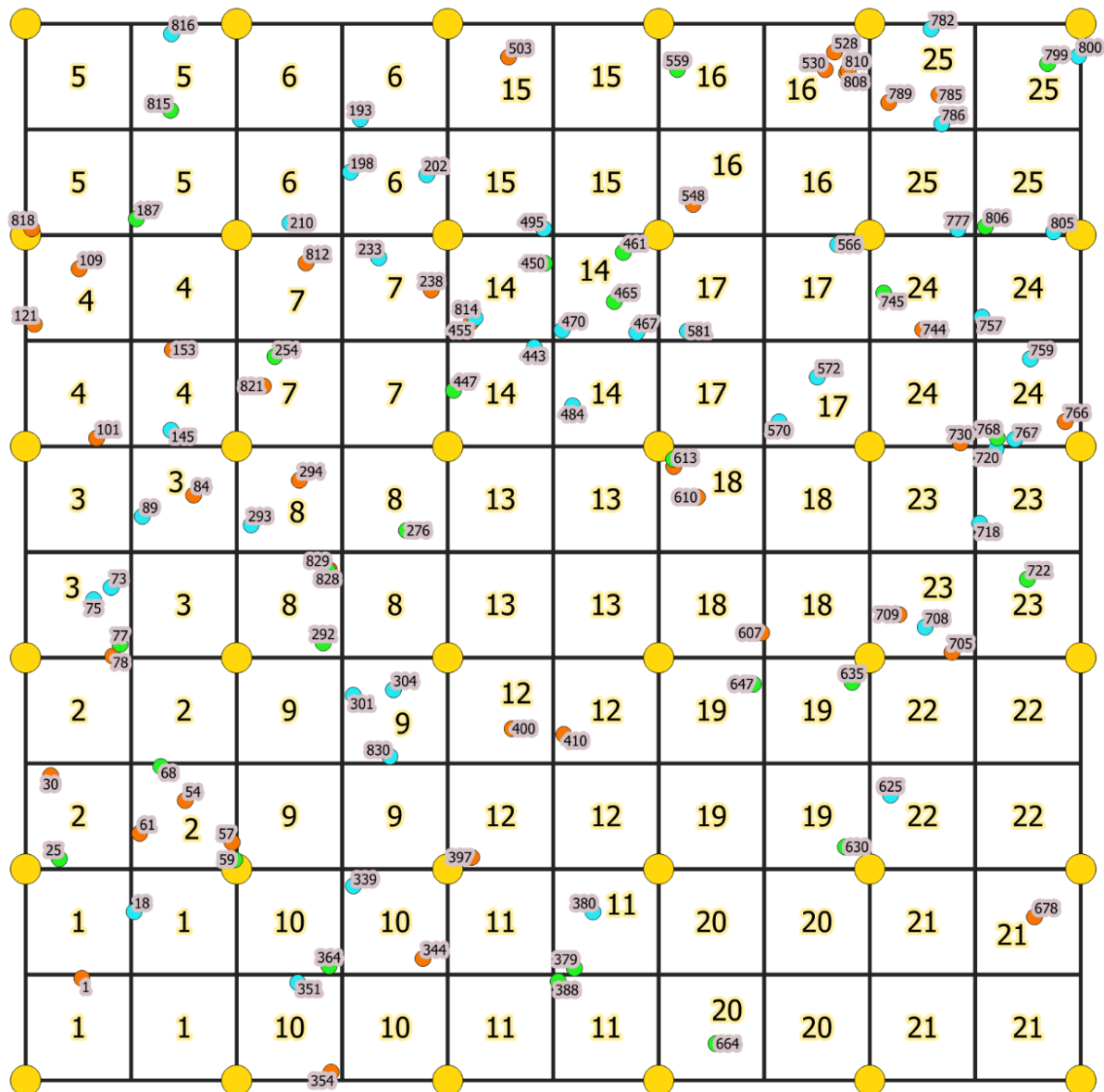
## Appendix 2

All the trees that were measured in the plot (tree ferns and palms included).



## Appendix 3

Trees who had their heights measured. Blue: Standard; Orange: Non-standard; Green: Random reference.



## Appendix 4

The prevalence of the exclusion characteristics among the 801 trees included in this study.

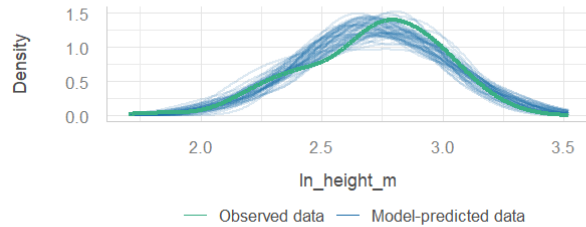
| Code | Characteristic | Number of trees | Percentage of all trees |
|------|----------------|-----------------|-------------------------|
| B    | Broken         | 20              | 2.5%                    |
| C    | Leaning        | 227             | 28.3%                   |
| D    | Fallen         | 5               | 0.62%                   |
| G    | Rotten         | 18              | 2.25%                   |

## Appendix 5

Control of linear model assumptions, for the (H:D) x Category allometric model.

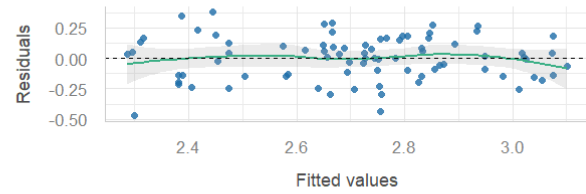
### Posterior Predictive Check

Model-predicted lines should resemble observed data line



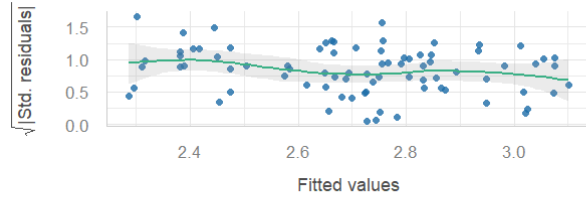
### Linearity

Reference line should be flat and horizontal



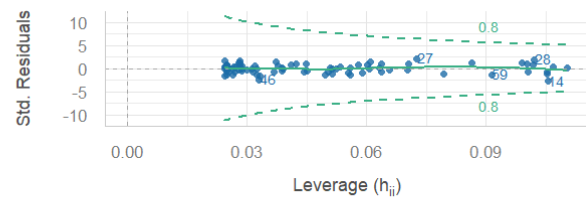
### Homogeneity of Variance

Reference line should be flat and horizontal



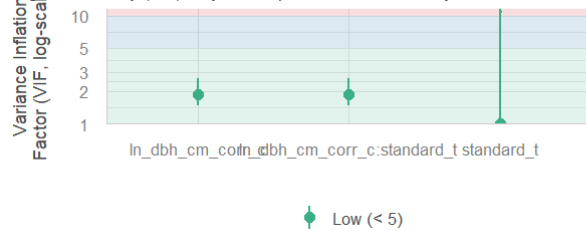
### Influential Observations

Points should be inside the contour lines



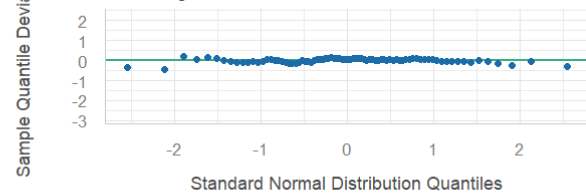
### Collinearity

High collinearity (VIF) may inflate parameter uncertainty



### Normality of Residuals

Points should fall along the line



## Appendix 6

Summary of the logarithmic centered model.

|                                                | Estimate | Std. Error | t-value | Pr(> t ) |
|------------------------------------------------|----------|------------|---------|----------|
| Geometric mean DBH: Standard                   | 2.76998  | 0.02861    | 96.809  | <2e-16   |
| Corrected DBH: Standard                        | 0.49511  | 0.05550    | 8.921   | 1.71e-13 |
| Geometric mean DBH: Non-standard<br>(compared) | -0.11475 | 0.04022    | -2.853  | 0.00556  |
| Corrected DBH: Non-standard<br>(compared)      | -0.16684 | 0.08161    | -2.044  | 0.04434  |