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# An accuracy analysis of mangrove tree height mensuration using forestry techniques, hypsometers and UAVs

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ABSTRACT

Tree height is a fundamental measurement in forest inventory studies and a critical variable for the assessment of tree biomass, carbon stock and site productivity. However, measuring tree height is often a challenging task and may generate errors. This study provides an accuracy analysis of tree heights measured through different methods ranging from traditional techniques (thumb rule and stick method) to trigonometric equipment (clinometer, laser rangefinder, altimeter), and advanced technologies (Unmanned Aerial Vehicle or UAV and distometer). Along with scientific insights for the in situ application of these methods, the factors generating errors in tree height mensuration and its impact on forest biomass estimation were determined. Our results showed that the amount of error varies from one method to another. The amount of error was highest with the thumb rule and stick method (15%) while the range of error was similar for the clinometer (7.7%), laser rangefinder (7.1%) and altimeter (7.5%). Parameters such as tree form, the status of tree (*i.e.*, if a tree was either isolated or within a canopy) and height of tree were found to significantly affect error generation during tree height measurements. Information on the extent to which biomass estimation is influenced by tree height errors associated with the use of different methods and instruments and the direction of error impact (overestimation or underestimation of biomass) are discussed. Finally, we recommend that the choice of method for tree heights in field inventory depends on certain factors such as cost, available time and manpower, required skills, site of observation and amount of error generated by each of the methods.

## 1. Introduction

Tree structure parameters are useful to evaluate the growth or maturity of a forest ecosystem. These parameters include tree height, tree diameter measured at 130 cm ($D_{130}$) above the soil and along the stem using a diameter tape (Dahdouh-Guebas and Koedam, 2006), absolute and relative density, absolute basal area (relative dominance), frequency of tree species and related structural characteristics. Among others, tree height is one of the basic measurements in forest inventory and is a vital variable in the quantitative assessment of forest biomass, carbon stocks, growth and site productivity (Andersen et al., 2006). The height of a tree is an indicator of its status within the population and is helpful in forecasting stand development and succession (Purves et al., 2008). Webster and Lorimer (2005) reported that the vertical structuring of trees determines the outcome of gap closure and the ability of understory species to reach canopy level. Further, height is assumed to

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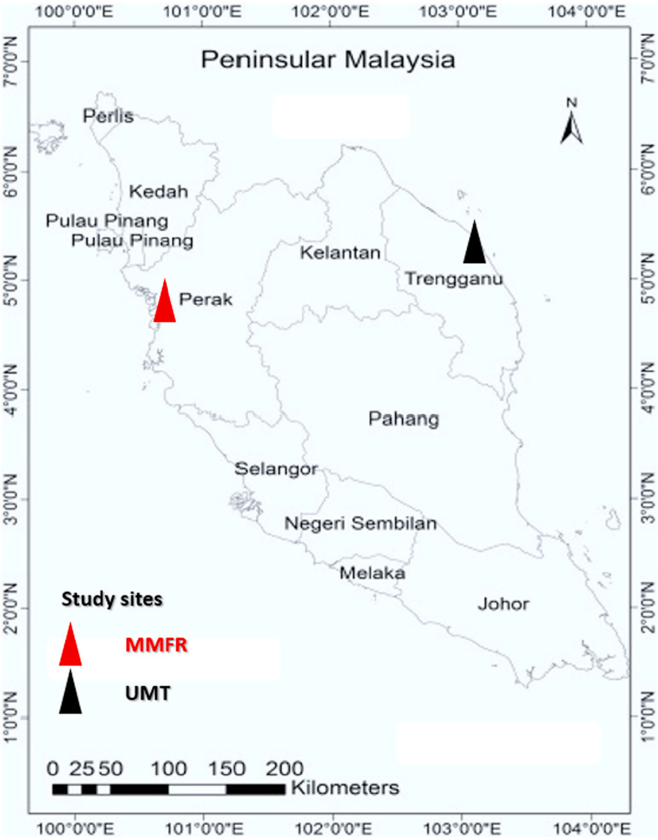

**Fig. 1.** Map of Peninsula Malaysia indicating the study sites located on the eastern and western coasts (adapted from Sabo et al., 2016).

be a major determinant of the ability of individuals of any given species to compete for light and could therefore offer information about an individual's position within the vertical light gradient of a given forest (Stereńczak et al., 2019). The effectiveness of the functional aspect of forest ecosystems depends largely on tree height. Changes in heights of trees are used in ecological studies dealing with life histories of individual trees and their populations (Larjavaara & Muller-Landau, 2013).

Tree biomass and carbon stock rely on field height measurements or estimates based on diameter–height allometry (Chave et al., 2005; Kauffmann & Donato, 2012; Hunter et al., 2013). Chave et al. (2005) reported that allometric equations with total tree height yielded less biased estimates of Above Ground Biomass (AGB), but tree height has often been ignored in carbon-accounting programs because measuring tree height accurately is difficult in closed-canopy tropical rain forests (Hunter et al., 2013; Larjavaara & Muller-Landau, 2013) or mangrove forests (Kauffman and Donato, 2012) and subject to random and directional error. Sullivan et al. (2018) reported that directional error will have the greatest consequence on local height - diameter equations, such that heights of trees are overestimated and hence biomass. This could be due to pinpoint discrimination of the topmost part of the tree from the ground (dense tropical forest), leaning nature of trees, multiple-stemmed or irregular form of trees (mangroves), crown spread, methodology used and human error. (Larjavaara & Muller-Landau, 2013; Stereńczak et al., 2019). These errors generate inaccurate figures which misrepresent the true nature of the species, confound conservation efforts (Blozan, 2006) and yield wrong biomass/volume estimation (Hunter et al., 2013).

This study focuses on the methodological approaches of tree height measurements. The height of a tree at a given time is constant. However, different techniques or instruments for measuring tree height may generate different results. This motivated us to carry out the present study to determine which method(s) generate the most accurate tree height measurement. Investigation on how certain measurement parameters such as the form of a tree (straight or lean trees), tree diameter, tree height and tree status (if a tree was isolated or within a canopy) affects the rate at which error is being generated from different methods was conducted. Further, error in tree height mensuration may result in wrong biomass estimation, hence, it is important to know the extent to which biomass estimation is affected by tree height error in ground inventory.

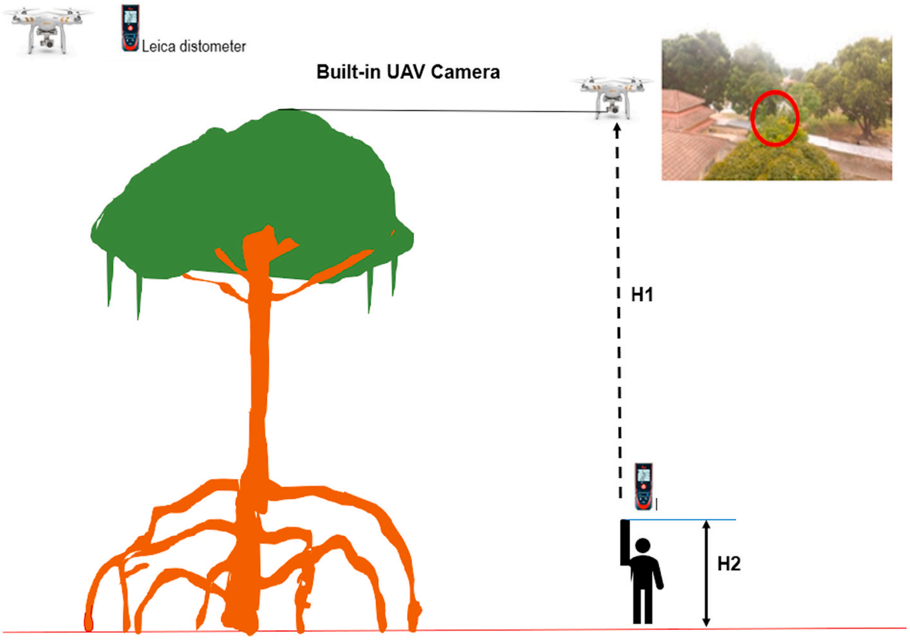

**Fig. 2.** Illustration of the use of the UAV and Leica distometer for measuring tree height. Monitor display of the UAV camera at the canopy layer of the tree; the red circle indicates the tip area of the tree. When the tip was visible on the display monitor, the Leica distometer was shot to the drone and its distance to the drone was measured as H1. The distometer was also used to measure its height above the ground level (H2). **Height of tree = H1 + H2.** (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

## 2. Materials and methods

### 2.1. Study areas

This research was conducted on the campus ground of Universiti Malaysia Terengganu (UMT), and in the Matang Mangrove Forest Reserve (MMFR), Kuala Sepetang, Perak, Malaysia. The UMT campus (05° 24.52′N and 103° 5.33′E) is in the state of Terengganu on the east coast of Peninsular Malaysia. It is located on the coastline of the South China Sea (see Fig. 1). The campus is comprised of academic and administrative buildings, research units, road networks, scattered mangrove vegetation structures and lakes that serve as habitats to local fauna (*e.g.*, monitor lizards, otters, snakes and different kind of birds). The MMFR (04°15’ – 05°1′N; 100°2’ – 100°45′E) lies in Perak state on the west coast of Peninsular Malaysia (see Fig. 1). A study conducted by Ariffin and Mustafa (2013) shows the division of the MMFR into four types of administrative zones: protective (17.4% of the total forest area in the Reserve), productive (74.8%), restrictive productive (6.8%) and unproductive (1%). Our sampling took place in compartment 19A (a section in the productive zone) and around the forestry department surroundings.

### 2.2. Sampling design

Tree height measurements on UMT and MMFR sites were performed with five different methods (*i.e.*, thumb rule, stick method, Suunto clinometer, Nikon 550 Forestry Pro laser rangefinder and Blume Leiss BL 60 altimeter) for this study. The use of poles for tree height measurements have been reported in past studies (Graves, 1906; Chapman and Meyer, 1949; Schreuder et al., 1993). However, within the scope of this study, poles were not included as part of the methods used due to its limitation of use for tall trees and in dense forests. An Unmanned aerial vehicle (UAV – DJI Phantom 3 Professional) and a Leica distometer were used to obtain the control heights of the trees. Trees were selected haphazardly in both locations and labelled with a permanent marker. Selected trees were either vertically straight (with the top vertically above the base) or with a slight lean (exhibiting not more than 5° inclination from the perpendicular). The distance at which heights were varied from one tree to another. The altimeter was used to measure tree heights at either 15 m, 20 m, 30 m or 40 m depending on where the operator could see clearly the treetop and tree base. The same distances were adopted for the clinometer and laser rangefinder. However, for the thumb rule and stick method, tree heights were measured at a distance where the operator could visibly pinpoint the treetop and tree base. Most times, this was farther than 40 m for trees within dense canopy .

To measure tree control heights, we flew the DJI Phantom 3 Professional from the base of the tree to the tip of the canopy vertically. The height of the UAV when it reached the highest tip was measured using a Leica distometer and taken as the control height for this study (Fig. 2). The Leica distometer was shot from the base of the tree to the base of the UAV when it reached the top of the tree. This was justified for several reasons. First, we could live track the video images of the drone using an on-board video camera viewing horizontally and see when it reached the highest branch tip. Second, climbing the tree is generally impracticable, and third, the Leica distometer had a ±3 mm accuracy (company-reported instrument error).

While it was impractical to affirm the alignment of the camera with the top of the tree, the camera was firmly positioned horizontally such that determining the tip of the tree when the UAV reaches the top of the tree was clear (Fig. 2). The distance of the UAV camera to the tip of the tree varied significantly for all trees depending on the wideness of the tree canopy and the overlapping of tree canopies. For trees with wide canopies, the UAV was flown a bit higher than the canopy (to investigate if there are no extended tips) before pinpointing the highest point of the tree. Further, tree tops were viewed from different sides of the trees to verify that the pinpointed tips are the correct ones. The same procedures were applied to trees with overlapping canopies. The UAV was not flown during windy situations to ensure the balance of the drone during flight, hence, wind sway had no impact on our measurements. While the entire procedure involving the use of UAV and distometer was extremely thorough, a speculated allowance of not more than ± 3° deviation for camera angle for over a maximum distance (to the tree tip) of not more than 10 m was considered where applicable (Appendix A, Table A1).

**Table 1**
Classification of different levels of factors that may influence error in tree height measurement.

| Factor | Levels |
|---|---|
| Angle of inclination | Straight trees = 0°; Lean trees = >1° to ≤5° |
| $D_{130}$ size class | <20 cm; 20–40 cm; >40 cm |
| Height categories | <10 m; 10–20 m; >20 m |
| Vegetation structure | Tree within a canopy; isolated trees |

Tree diameter at 130 cm ($D_{130}$) above the soil and along the stem was measured for all trees using a diameter tape (Dahdouh-Guebas and Koedam, 2006). The angle of inclination was used as a proxy to measure the form of trees (straight or leaning trees). This was done by placing a steel protractor (120 by 150 mm) at the base of the tree, and the angle at which the tree deviates from straightness (90°) was recorded. The limitation of this method was such that accurate measurement of angle of inclination may not be possible for trees straight at the base but starting to lean at a certain distance above the reach of the protractor.

### 2.3. Data analyses

#### 2.3.1. Accuracy tests and percentage error generated by different methods

Descriptive analyses (mean, count and standard deviation) and tests for significant differences between measured heights from different methods and control heights were conducted for all study sites. A Shapiro-Wilk test was used to check for normality of residuals and a Levene test for homogeneity of variance was performed to verify the assumptions of ANOVA. In cases where the assumptions were not met, a non-parametric Kruskal-Wallis test was conducted. For independent comparison of the means of measured heights from different method and the control heights, a parametric paired t.test was performed in cases where t.test assumptions were met and a non-parametric paired t.test (Wilcoxon signed-rank test) was carried out in cases where assumptions (normal distribution and homogeneity of variance) were not met. Further, a simple linear regression was used to show the goodness of fit through the coefficient of determination ($R^2$) and Pearson correlation of measured heights with the control heights. This was done to see which of the methods produced results that are closest to the control heights. The deviation of the measured heights from the control height was expressed as percentage error (Eq. (1)) to understand the percentage overestimation and underestimation of height, and the amount of error generated by each method.

$$\frac{\textit{Measured height} - \textit{Control height}}{\textit{Control Height}} \times 100 \tag{1}$$

#### 2.3.2. To investigate the effect of measurement parameters on percentage error

A non-parametric test (Kruskal-Wallis chi-squared test) was performed to investigate the effect of parameters such as: form of tree using the angle of inclination (straight trees or leaning trees), tree height categories, tree diameter size class and tree status (isolated or within a canopy) on percentage error generated from different methods of tree height measurement. Each parameter was considered as a factor and divided into different levels (Table 1). The interaction of each parameter with the different methods was visualized on an interaction plot.

#### 2.3.3. Test for the effect of tree height error on biomass estimation

To determine the extent to which tree height error may affect

**Table 2**
Descriptive statistics showing coefficient of determination ($R^2$) as a measure of degree of fitness; counts; mean; standard deviation (SD); Wilcoxon signed-rank test (p-value) showing difference between measured heights and control heights; test statistic (V) which is based on pairwise difference between the individuals in two groups *e.g.* difference between stick and control heights; and P-values.

| Methods | $R^2$ | Count | Mean | SD | (V) | P-value |
|---|---|---|---|---|---|---|
| Thumb rule | 0.79 | 173 | 9.46 | 3.93 | 2845.5 | <0.0001 |
| Stick | 0.86 | 173 | 11.4 | 4.94 | 11879 | <0.0001 |
| Clinometer | 0.93 | 173 | 10.5 | 4.07 | 7967 | 0.503 |
| Laser rangefinder | 0.96 | 173 | 9.89 | 3.92 | 1587.5 | <0.0001 |
| Altimeter | 0.94 | 173 | 10.1 | 3.94 | 4039.5 | <0.0001 |

biomass estimation, the measured heights from each method were used independently to estimate the biomass of 27 *Rhizophora apiculata* trees (MMFR) using the equation (Eq. (2)) adapted from Kauffman and Donato (2012) and compared with the biomass estimation using the control height:

$$\boldsymbol{biomass}\ (\boldsymbol{kg}) = 0.0444 \times \{\boldsymbol{D}^2\boldsymbol{H}\}^{0.96842} \times \boldsymbol{\rho} \tag{2}$$

where **D** = tree diameter at 130 cm from base along stem (cm), **H** = tree height (m), and $\boldsymbol{\rho}$ = wood density (g/cm $^3$).

Wood density ($\rho$) of *Rhizophora apiculata* = 1.050 g/cm $^3$ (Simpson, 1996).

The deviation of the measured biomass from the actual biomass was expressed as a percentage of the actual biomass. This showed the amount of underestimation or overestimation of biomass associated with the use of different methods.

$$\frac{\textbf{\textit{Measured biomass}} - \textbf{\textit{Actual biomass}}}{\textbf{\textit{Actual Biomass}}} \times 100 \tag{3}$$

Descriptive statistics, data analyses, tests and visualization of results using graphical illustrations were conducted in Microsoft Excel and R studio (version 1.1.463 – R Development Core, 2011).

## 3. Results

### 3.1. Accuracy, precision and percentage error of tree height methods

A total of 173 trees were measured (UMT = 146; MMFR = 27). A Shapiro-Wilk test revealed that the residuals of measured height were not normally distributed, (Shapiro.test, $W = 0.926$, $p < 0.0001$), therefore, a non-parametric test conducted showed a significant difference between measured tree heights from different methods (Kruskal-Wallis chi-squared = 21.336, d.f. = 5, $p < 0.05$). Also, a Wilcoxon signed-rank test revealed that a significant difference existed between the measured heights and control heights for all methods except the clinometer (Table 2). The coefficient of determination ($R^2$) showed that the best method for tree height measurement was the laser rangefinder ($R^2 = 0.96$, $p < 0.0001$) and the least accurate method for tree height measurement was the thumb rule ($R^2 = 0.79$, $p < 0.0001$; Fig. 3b).

Overall, the choice of method had a significant effect on the amount of error generated during tree height measurements (Kruskal-Wallis chi-squared = 21.34, d.f. = 5, $p < 0.05$). The thumb rule and stick method generated the highest amount of error (~15%) while the amount of error generated by the clinometer, laser rangefinder and altimeter were less than 10% (7.7%, 7.1% and 7.5% respectively; Fig. 4).

### 3.2. Effect of measurement parameters on amount of error generated

#### 3.2.1. Angle of inclination

The form of a tree (angle of inclination) had a significant effect on the amount of error generated from the different methods during tree height measurements (Kruskal-Wallis chi-squared = 7.71, d.f. = 1, p = 0.01). An underestimation of tree heights was observed with the increasing angle of inclination by the thumb rule, altimeter and laser rangefinder. The clinometer overestimated measured tree heights with increasing angle of inclination and generated absolute error up to 8% in leaning trees (Fig. 5a).

#### 3.2.2. Tree diameter size

The size of a tree had no significant influence on the amount of error generated from different tree height methods (Kruskal-Wallis chi-squared = 0.17, d.f. = 2, p = 0.92). The altimeter and laser rangefinder underestimated tree heights, generating ~7% absolute error and was not affected by the different diameter sizes. The overestimation of tree heights by the clinometer was minor and constant for all trees regardless of diameter sizes. While all trees were overestimated by the stick method, big trees (> 20 cm $D_{130}$) were overestimated more often than smaller trees. Height of trees were underestimated by the thumb rule. Further, an increased underestimation was observed with increasing tree size by the thumb rule (Fig. 5b).

#### 3.2.3. Tree height categories

The height of a tree influenced significantly the amount of error generated from different methods during tree height measurements (Kruskal-Wallis chi-squared = 11.80, d.f. = 2, $p < 0.05$). The altimeter and the laser rangefinder underestimated heights of trees especially in trees shorter than 10 m and trees taller than 20 m (error ~8%). An overestimation with increasing tree heights was observed by the clinometer. The amount of error generated by the clinometer and laser rangefinder was higher in trees < 10 m and trees > 20 m (~8%). More than 15% absolute error was associated with the use of the stick method and height of taller trees (> 10 m) were overestimated more frequently by the stick method (Fig. 6a). A pronounced underestimation of trees heights was observed by the thumb rule in shorter (< 10 m) and taller trees (> 20 m) .

#### 3.2.4. Status of tree

The error generated from different methods was significantly affected by the status of tree (Kruskal-Wallis chi-squared = 18.71, d.f. = 1, $p < 0.05$). Heights of isolated trees were underestimated by the altimeter, laser rangefinder and the thumb rule (Fig. 6b). Additionally, heights of trees in a closed canopy were overestimated by the clinometer (error ~7.5%). The stick method overestimated tree heights both for trees in closed-canopy (error ~13%) and isolated trees (error ~15%).

### 3.3. Effects of tree height error on biomass estimation

The AGB for 27 *Rhizophora apiculata* trees using the control height was 8975.69 kg. This was overestimated up to ~7% when the heights were obtained from the clinometer (biomass = 9568.25 kg) and up to 2% when heights from the laser rangefinder (biomass = 9157.42 kg) were used. However, an underestimation of the biomass up to 1.2% was observed with the heights obtained from the altimeter (biomass = 8865.75 kg). Further, the stick method underestimated biomass up to ~12% (see Fig. 7).

## 4. Discussion

### 4.1. Accuracy and percentage errors of different tree height methods

This study showed that the amount of error generated during tree height mensuration varied with the choice of method, thus affecting the accuracy of the method or instrument used. This is in contrast with a recent study (Stereńczak et al., 2019) stating that the type of device used has a negligible relative impact on the accuracy of tree height measurements. The thumb rule and the stick method generated the highest amount of error while the clinometer, laser rangefinder and altimeter generated a lesser amount of error with reference to the control heights for this study (Fig. 4). Due to the impracticability to harvest trees for the

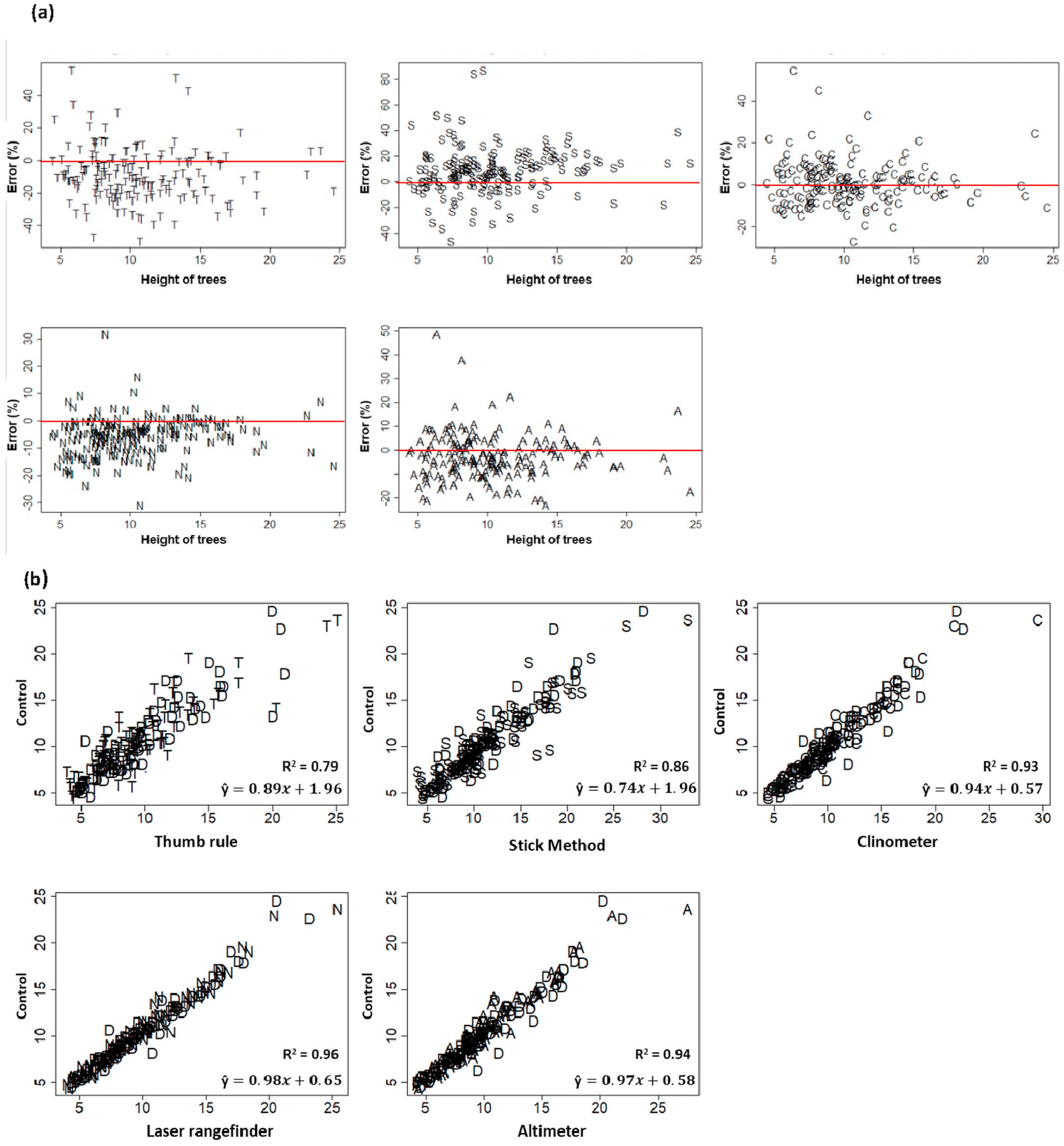

**Fig. 3.** a: Graphical representation of overestimation and underestimation (%) of measured heights from different methods – thumb rule (T), stick method (S), clinometer (C), laser rangefinder (N) and altimeter (A). Red dashed line "——" indicates the point where measured heights = control heights. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.) 3b: Scattered plots of measured heights from different methods versus control heights with the linear regression equations. Each point represents the height of a tree measured with different methods: thumb rule (T), stick method (S), clinometer (C), laser rangefinder (N), altimeter (A), control (D).

sole purpose of the research – one of the study sites was under a 30-year rotational program (MMFR) while the other was on a university campus (UMT) – control heights were obtained from the UAV and a Leica distometer. Further, we aimed to propagate the potential of obtaining actual tree heights without destructive means.

Over the years, exploitation of remote sensing devices such as satellites, aircrafts and unmanned aerial vehicles (UAVs or drones) serving as platforms for different sensors (e.g. laser and optical sensors) for forest inventory has increased tremendously due to increase in technology and its cost-effectiveness (Andersen et al., 2006; Fatoyinbo et al., 2013; Sibona et al., 2017; Otero et al., 2018; Doughty and Cavanaugh, 2019). While aerial photography is the most common use of a

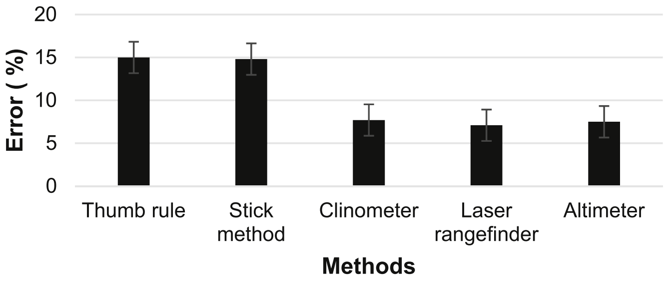

**Fig. 4.** Average percentage error of tree heights generated by different methods for tree height measurement.

UAV or drone, many of the models available (e.g. DJI 3 Phantom Professional) are also capable of measuring altitude or the height of the drone above ground (Kulhavy et al., 2017), and implementing photogrammetry due to low-cost and off-the-shelf digital cameras (Manfreda et al., 2018).

#### 4.1.1. *Thumb rule and stick method*

The high error generated from the thumb rule and stick method could have been from different sources. Masking the entire height of the tree with the thumb or stick requires the observer to move very far away from the tree, especially for tall trees. The thumb rule and stick method do not always fix steadily with the top (due to windy conditions) and base of the tree, especially in a dense canopy with tall undergrowth, and thus, may not represent the real height of the tree when positioned horizontally. Light winds have been reported to cause the treetops to sway several decimeters (Andersen et al., 2006) and the presence of

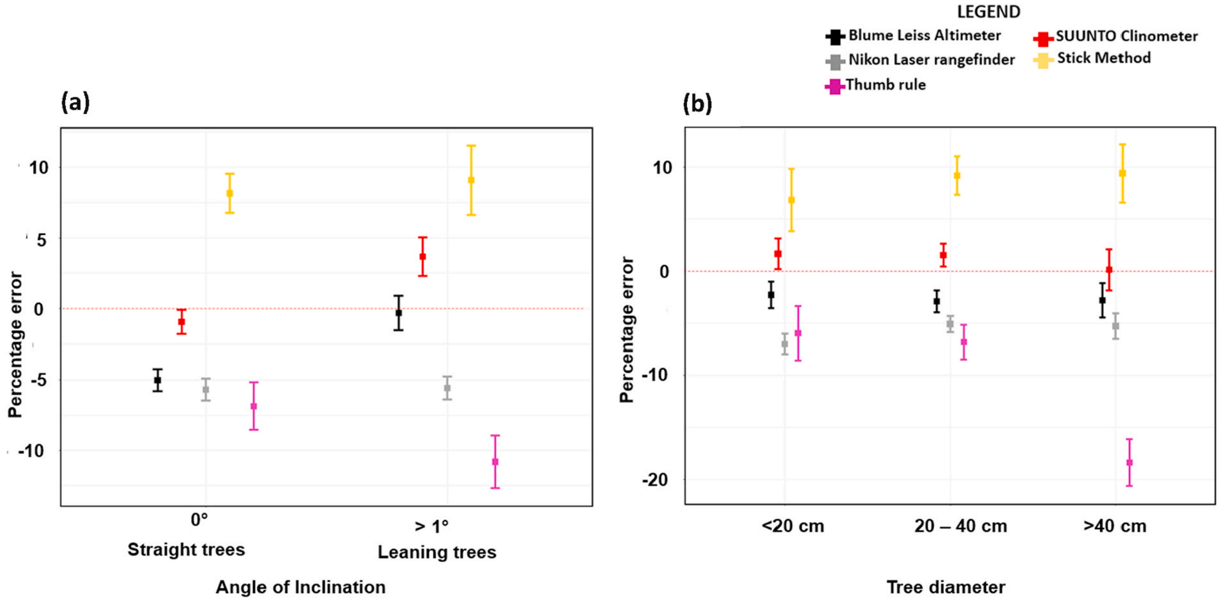

**Fig. 5.** Percentage overestimation and underestimation of tree height from different methods at (a) angles of inclinations: Straight trees = 0° and Lean trees = > 1° to ≤ 5°; (b) trees diameter size classes: < 20 cm, 20–40 cm, > 40 cm. Red dashed line "——" indicates the point where measured heights = control heights. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

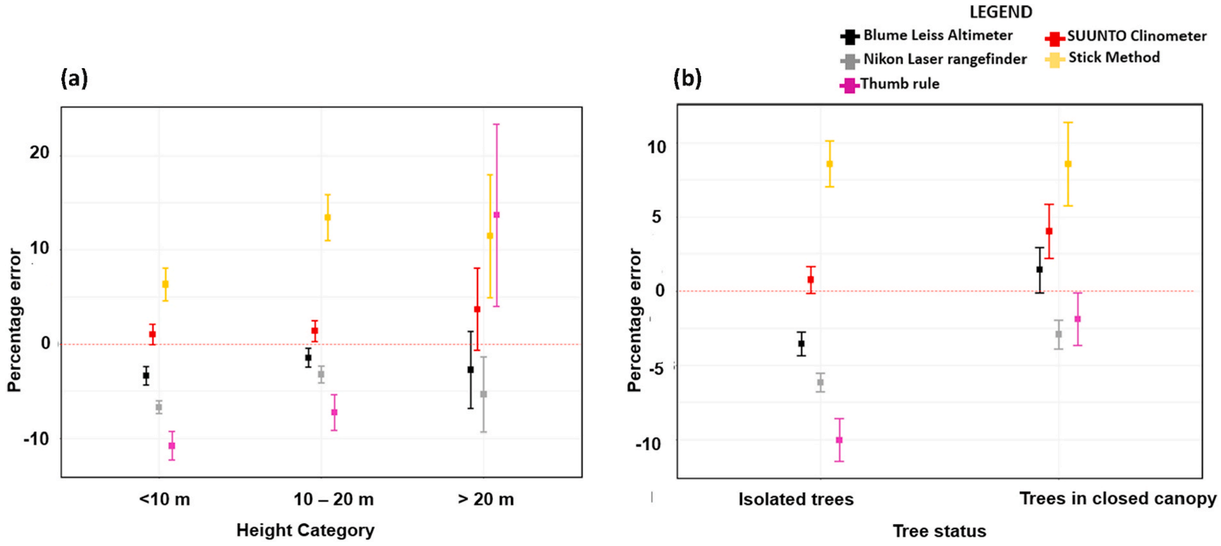

**Fig. 6.** Percentage overestimation and underestimation of tree height from different methods at (a) different height classes: < 10 m, 10–20 m, > 20 m; (b) different tree status: isolated trees and trees in closed canopy (Red dashed line "——" indicates the point where measured heights = control heights). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

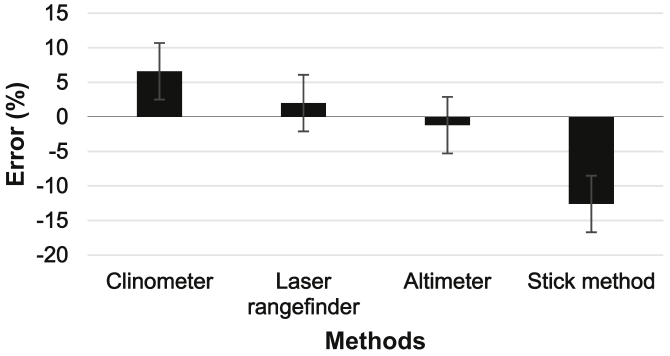

**Fig. 7.** Bar chart showing the effect of tree height error from different methods on biomass estimation. Error bars indicate standard error.

undergrowth may also pose a problem when finding a landmark on the ground to mark the tip of the thumb when placed horizontally. There were cases during our field work in which fellow colleagues, acting as a landmark, could not be seen in the tall undergrowth by the operator. This was not an issue with isolated trees. However, on the UMT campus, certain obstructions such as administrative buildings posed as potential obstructions. Further, the presence of roads affected the measurement efficiency as the operator would have to wait for little or no traffic in order to proceed with the measurements. This reflects the challenge posed by using the thumb rule and stick method for inventory on a large scale and why they required more time than the other methods.

Moreover, the use of a tape to measure the distance of the observer from the tree during the implementation of the stick method proved difficult under certain conditions (*e.g.*, in the muddy terrain of the mangroves, dense stands and tall undergrowth or piles of felled *Rhizophora apiculata* trees in the MMFR). This challenge extended to the use of the clinometer, laser rangefinder and the altimeter in the closed dense canopy. Even though the laser rangefinder was used to measure the distance in these conditions, care was taken, and more time was spent on finding a path with no obstacles between the observer and the target tree. In isolated trees, the use of tape for measuring distance was easy but time consuming and required more than one observer to achieve. On the other hand, the procedure for measuring distance with the laser rangefinder was also straightforward and easy. However, care should be taken when measuring distance to some trees (*e.g.*, King Palm (*Archontophoenix cunninghamiana* (H.Wendl.) H.Wendl. & Drude on the UMT campus). If trees are measured during the brightest hours of the day, the grey stem color of *A. cunninghamiana*, coupled with the irradiating effect of the sun, resulted in failed measurements of the laser rangefinder. Bright coloured target and shiny exteriors are listed as factors that affect measurement, range and accuracy of the laser rangefinder (Nikon Vision Ltd., 2018).

#### 4.1.2. *Clinometer*

The amount of error generated by the clinometer was higher in trees $< 10$ m and trees $> 20$ m ($\sim$8%). This is similar to the results of Williams et al. (1994) who reported that a significant bias is associated with the use of clinometer for trees $< 33$ ft ($<$10.05 m) and $> 66$ ft ($>$ 20.11 m) during an accuracy test for five tree height instruments (Suunto clinometer, Seigel relaskop, Speigel tele-relaskop, Enbeeco clinometer and a Laser height finder). Hyyppä et al. (2000) suggested that accuracy of height estimation using a clinometer for trees taller than 25 m can be up to 1 m, and Hunter et al. (2013) reported that the use of clinometer may result in a less precise measurement of tall trees than short trees. The tangent method with the clinometer from our study caused an overestimation in tree heights with increasing angle of inclination (lean), tree diameter and in closed canopy. This aligns with Bragg (2008) who reported an overestimation of a leaning southern red oak (inclination of 20° from the vertical) when it was measured at the point perpendicular to the lean and when the lean was directed towards the observer. Our study did not discuss the effect of leaning direction on the amount of error generated, however, we acknowledge that different results may be generated when measuring the height of a tree leaning towards the observer, away from the observer or towards the side.

Although our study utilized the tangential method of height estimation with the clinometer, recent research recommends a sine-based, as opposed to a tangential, method for deriving tree height (Bragg, 2008; Bragg et al., 2011), stating that a very large proportion of lean trees have bends or angles in their upper boles or are found on sloping ground. These deviations from the ideal scenario make it necessary to take corrective actions to predict true height using the tangent method. Most of the assumptions were met to the best of our knowledge during the use of the tangential method, as the operator stood on the same ground level as the trees and readings were only taken from the clinometer when both the top and the base of the tree were clearly visible (even in the closed canopy of the MMFR). However, others concluded that the sine method is also biased and should be treated rather as an alternative, in the absence of systematic corrections (Larjavaara & Muller-Landau, 2013).

The sine method by Larjavaara and Muller-Landau (2013) adopted the use of a Nikon 550 Forestry Pro laser rangefinder (the same as this current study) rather than the Suunto clinometer to measure the angle to the top of the tree and recorded an underestimation of trees heights. When the laser rangefinder mode was set at Hgt-Hgt2, this denoted the vertical separation between 'treetop' (Hgt) and 'tree base' (Hgt2), tree heights were still underestimated (which agrees with our current findings) but was less severe when compared with the sine method. The study further emphasized that the accuracy of the Hgt-Hgt2 mode might have resulted from being used for trees that were easier to measure and not because it is superior to the sine method. Additionally, the study by Larjavaara and Muller-Landau (2013) observed an overestimation of tree heights with the tangent method due to angles over 70° shooting to the top of the tree and short distance of the observer from the tree. This could be that the observer shot too high up, probably trying to figure out which part of the crown was directly above the base. The possibility of this source of error can be ruled out of our study as the angle shot to the top did not exceed 45° as recommended by Goodwind (2004). The main reason for this recommendation is that the tangent of an angle increases very rapidly for larger angles, and thus, the accuracy of the height measurement declines disproportionately.

Further, distance measurement is also affected by obstacles. The distance from the tree varied from one tree to another. Tree heights were measured at a distance where the operator could clearly see the treetop and tree base. When pulling a measuring tape through the forest, it is necessary to weave through understory vegetation and other trees and the use of laser range finder requires finding a clear path in the vegetation to the target tree. Moreover, differences between the distance measured and the true horizontal distance to the crown can cause an unbiased error in height measurement. Also, ground slope if not properly accounted for, might result in overestimation of distance which causes overestimation of heights (Blozan, 2006; Bragg, 2008; Hunter et al., 2013). Few people adjust for ground slope, tree lean or skewed crown apex in the field (Bragg 2008), but cheap laser distance measuring equipment is now available and can be used to measure the slope distance to the highest and the lowest points of the tree.

Another source of error for the clinometer when using the tangent method and other methods occurs when an observer or recorder either transposed numbers or omitted a negative sign while recording the data (Larsen and Hann, 1987). However, the protocol we followed in the field while measuring with the clinometer required measuring the angle to only the top of the tree (base angles are mostly negative), after which the height of the observer's eye level was added to the estimated tree height. Moreover, all readings were recorded in a pre-made work sheet and verified for a tree before moving to the next one.

### 4.1.3. Laser rangefinder

The laser rangefinder underestimated tree heights in all cases. This agrees with previous results from Larjavaara and Muller-Landau (2013). It generated the lowest amount of error (Fig. 4) and had the strongest correlation with the control heights. The laser rangefinder can be said to be more accurate (Božić et al., 2005) because it takes into consideration the slope of the ground when measuring the angle to the top, angle to the base and the horizontal distance to the tree (Bragg 2008, 2011). The use of the laser rangefinder is advantageous since the device automatically computes the height of the trees as opposed to manual extrapolation of the tree height using tangent, sine or other conventional methods (Blozan, 2006).

The error generated by the laser rangefinder in our study could have been because the highest points of the trees were not directly above the base of the tree. Another major problem with the laser rangefinder is that it has a wider laser beam dispersion and does not work well when shooting through tight openings or where there are intervening bush or branches (Frank, 2010). This was a major challenge in closed canopy trees (MMFR). The laser rangefinder presented certain challenges when used to measure distance to the stems of some isolated trees (on UMT campus) due to the absorption of the laser rather than bouncing off the trees. However, this had no impact on shooting to the top and base of the tree for angular measurements for both sites.

Further, errors could be generated from the laser rangefinder by negligence on the path of the operator (Bragg, 2008) in certain study areas. The device allows for different modes: First Target Priority ($1^{st}$) and Distant Target Priority mode (Dst). The First Target Priority mode allows the laser to hit the first object on its path while the Distant Target Priority mode allows the laser to hit objects beyond the first target. Inadequate knowledge of these modes on the part of the operator may generate systematic errors, especially in dense and closed canopy forests. In a closed canopy, using the laser rangefinder might be very tricky because being able to ascertain the exact point of the tree can be problematic. Thus, the possibility of shooting to a wrong part of the tree or the tip of another tree is imminent. This was tackled by carefully scanning the treetop with the device and taking multiple readings to ensure certainty.

Additionally, it was almost impossible to shoot to the base of the tree due to dense undergrowth along the path of the laser to the target tree. In such cases, a clearly visible point on the stem was chosen by the operator as the base of the tree, marked, and a meter rule was used to measure the height of the point above the base of the tree, and added to the height obtained from the laser rangefinder. This was also applicable to the clinometer and altimeter. The other concern is that it is less obvious to notice if mistakes are being made with the use of the device. There is a tendency to just shoot the height of a tree, write down the measurement and move on to the base. There is a possibility of hitting a forward leaning branch, or a branch on another tree, or an intervening branch rather than the exact tip (Frank, 2010).

### 4.1.4. Altimeter

Generally, the altimeter underestimated trees heights in all cases. As the same principle regarding clear visibility to the treetop and base as the other methods applies to the altimeter, the procedure for using the altimeter was quite clear. However, it could be tricky for new users due to the possibility of mixing up the buttons during measurement (*i.e.*, there is a chance that an operator presses the upper white button instead of the lower white button when shooting to the base of the tree and *vice versa*). This may generate significant errors which reduce accuracy of height measurements. Further, it was observed during our field work that after a certain amount of height measurement with the altimeter, the needles tend to freeze at certain points and does not move freely, thus resulting mostly in underestimation of tree heights. This may be continuous and lead to a large amount of error if not quickly detected. Therefore, it suffices that a second observer monitors the movement of the needles in the device when it is in use.

Measuring tree height at a fixed distance of either 15 m, 20 m, 30 m or 40 m also posed a challenge as there were times when the perfect distance for viewing the top and the base of some trees especially in dense canopy, was either a little bit more or less than any of the recommended distances. This resulted in the rejection of certain trees as samples. The different distances correspond to different scales on the device through which the height of the tree being measured can be read directly. Hence, errors could be generated from reading tree heights from scales not corresponding to the actual distance at which the observer is standing from the tree. This may require that the observer carefully view the scales before recording the tree height.

## 4.2. Effect of tree height error on biomass estimation

Previous studies have shown that tree heights improve biomass estimates as compared with diameter only in allometric relations for tropical forest trees (Chave et al., 2005; Hunter et al., 2013; Phalla et al., 2017; Ekoungoulou et al., 2018; Xu et al., 2019). Quite a number of studies on biomass estimation with tree heights used only one method to measure tree height with most studies using the clinometer for tree height mensuration (Hunter et al., 2013; Sullivan et al., 2018; Bhatta et al., 2018; Dube et al., 2018; Kim et al., 2018; Muhati et al., 2018; Fajardo, 2018; Latifah et al., 2018; Owino et al., 2018; Barbosa et al., 2019). Few studies used different forms of hypsometers varying from Haglof Vertex III to Nikon Forestry Pro (Kearsley et al., 2013; Wu et al., 2016; Sullivan et al., 2018; Ekoungoulou et al., 2018) and to different models of Blume Leiss altimeters (Lim and Cousens, 1986; Williams et al., 2003; Kitikidou et al., 2014; Hirankhede et al., 2017; Padmakumar et al., 2018). Generally, most of these studies only focus on evaluating the suitability of including tree height in allometric equations for biomass estimation. Even though they acknowledged the challenges facing the acquisition of accurate heights in ground inventory for biomass estimation, only Hunter et al. (2013), Tompalski et al. (2014) and Sullivan et al. (2018) had estimated the effect of tree level uncertainty in height on estimation of biomass. Thus, this current study provides information on the extent to which biomass estimation is influenced by tree height errors associated with the use of different methods and instrument (stick method, Suunto clinometer, Nikon 550 Forestry Pro laser rangefinder and Blume Leiss BL 60 altimeter).

The uncertainty of height measured with the clinometer resulted in an overestimation of biomass up to about 7% for the *Rhizophora apiculata* trees in the MMFR. This is similar to the Hunter et al. (2013) study results which reported that error from height measurement causes a small error (5% to 9%, mean of 6%) in transect level biomass. Error from measured heights with the laser rangefinder and altimeter generated less than 2% error in biomass estimates, which could mean that the use of both equipment for height mensuration could have no or little impact on biomass estimation. The number of trees ($n = 27$) measured for this purpose could be a factor governing the presented results. A recent study by Sullivan et al. (2018) reported decline in biomass error with increasing sample size and recommended sampling 50 trees as a conservative threshold. Error in height measurements from the stick method resulted in an underestimation of tree height up to about 12%, making it a method whose impact on biomass estimation may critically affect management decision making.

## 5. Conclusion and recommendations

This study conducted an accuracy analysis of tree heights obtained from different methods, examined the technicality behind the application of the methods in the field and determined the factors governing error generation and how tree height error influences biomass estimation in ground inventory. Our results demonstrated that the amount of error generated varies from one method to another and could be influenced by certain factors such as tree lean, status of tree (*i.e.*, if a tree was either isolated or within a canopy) and height of tree. This study

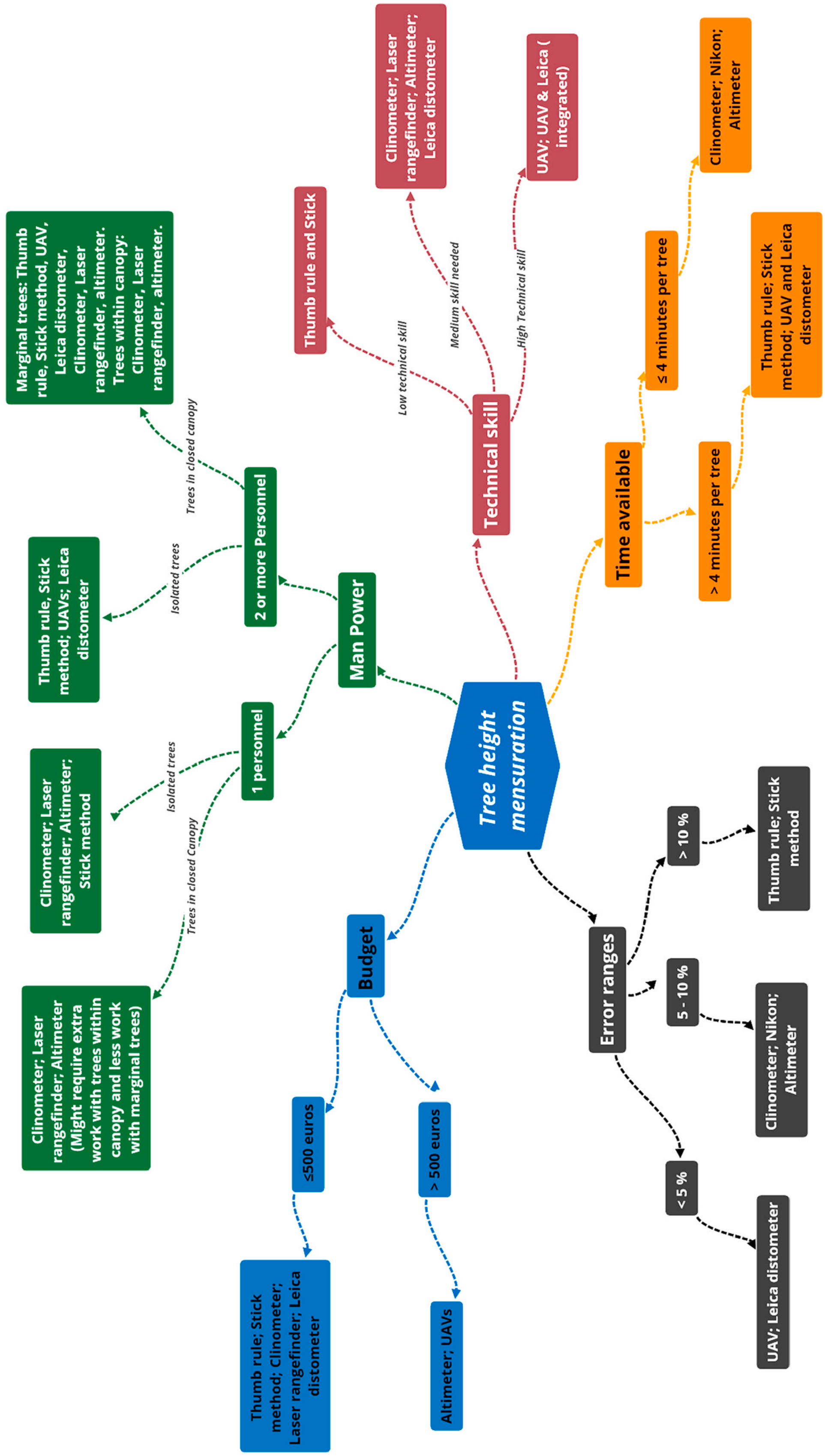

**Fig. 8.** A guide chart for choosing appropriate methods for tree height mensuration based on current study. Each color palette represents a factor that may influence the choice of methods. Factors include budget (blue), manpower (green), technical skills (brown), time available per tree (orange) and error range of each method (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

provides information on the extent to which biomass estimation is influenced by tree height errors associated with the use of different methods and instrument and the direction of error impact (overestimation or underestimation of biomass).

The potential of UAVs and Leica distometer as a means of getting true heights of trees was highlighted as it imitates tree climbing but is less risky and saves time. However, certain limitations such as losing connection with control, flying propellers hitting personnel or animals, expertise and training time required, rules and regulations governing flight in certain locations and the cost of purchase are associated with the use of the UAVs. Further, we recommend that the choice of method for tree heights in field inventory depends on certain factors as laid out (Fig. 8), but consideration should be given to the amount of error generated by each of the methods. Other factors such as the price of the equipment (budget), skills required to operate the equipment, time required per tree to measure using the equipment and the manpower required to use the equipment should be considered with reference to the management objectives and the aim of conducting forest inventory. The fragility of equipment should be carefully considered during forest inventory as certain equipment (*e.g.,* laser rangefinder, altimeter, UAV and distometer) could be damaged easily due to contact with salt water in the mangroves. Manual alternatives such as the clinometer and stick method could offer more robust usage in areas with such conditions.

Finally, we propose that the knowledge and direction of the error generated by each method could enhance accuracy in height measurement. For example, since our study and previous study have reported the clinometer to overestimate tree heights, and the clinometer generates about 7% error, a better estimation of height with the clinometer would be:

$$\textbf{\textit{Total tree height}}\ (\boldsymbol{H}) = (\boldsymbol{H}1 + \boldsymbol{H}2) - 0.07(\boldsymbol{H}1 + \boldsymbol{H}2) \tag{4}$$

$$\boldsymbol{H}1 = \boldsymbol{D} \times \boldsymbol{Tan}(\boldsymbol{\alpha})$$

*where*, H1 = Height of the tree from the observer's eye level, H2 = Height of observer eye level, D = Distance of observer from tree (baseline distance) and α = Angle to the top of the tree.

This is a suggestion and could be applied to the other methods given that the amount of error generated by the methods is known and direction of error is constant.

Future research aims to investigate the effect of human error on the mensuration of tree height and the precision of tree heights measured multiple times with different equipment.

## Credit author statement

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## CRediT authorship contribution statement

**Ibrahim Sunkanmi Saliu:** Methodology, Data curation, Resources, Validation, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Behara Satyanarayana:** Conceptualization, Methodology, Resources, Validation, Investigation, Supervision, Project administration, Funding acquisition, Writing - review & editing. **Muhammad Amir Bin Fisol:** Investigation, Data curation, Writing - review & editing. **Giovanna Wolswijk:** Validation, Investigation, Visualization, Writing - review & editing. **Charles Decannière:** Validation, Supervision, Writing - review & editing. **Richard Lucas:** Conceptualization, Methodology, Validation, Supervision, Project administration, Writing - review & editing. **Viviana Otero:** Validation, Supervision, Project administration, Writing - review & editing. **Farid Dahdouh-Guebas:** Conceptualization, Methodology, Resources, Validation, Investigation, Supervision, Project administration, Funding acquisition, Visualization, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2020.106971.

## Appendix A

**Table A1**

Errors (in m) as a function of camera angle and UAV-tree tip-distance. Horizontal camera angles are error-free. Errors are shaded per class of 0.5 m. We estimate that our errors are limited to camera angles of 3° or less and UAV-tree tip-distances of 10 m or less for trees at least 13 m tall and of UAV-tree tip distances of 5 m or less for trees under 13 m tall, *i.e.* the two boxes shaded in yellow. Hence, to understand the significance of an error, it should be checked against the height of the tree (*e.g.* 0.2 m error on a tree of 3 m tall is significant whereas on a tree of 20 m tall it is not). In an *a posteriori* check, we found that in a total of 197 measurements, only 5 measurements had 5% chance of having a significant error, which is considered negligible.

(*continued on next page*)

**Table A1** (*continued*)

| | | Camera angle(°) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Camera angle(°) | | | | | | | | | | |
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 9 | 9 | 10 |
| ;Distance to tree tip (m) | 1 | 0.00 | 0.02 | 0.03 | 0.05 | 0.07 | 0.09 | 0.11 | 0.12 | 0.16 | 0.16 | 0.18 |
| | 2 | 0.00 | 0.03 | 0.07 | 0.10 | 0.14 | 0.17 | 0.21 | 0.25 | 0.32 | 0.32 | 0.35 |
| | 3 | 0.00 | 0.05 | 0.10 | 0.16 | 0.21 | 0.26 | 0.32 | 0.37 | 0.48 | 0.48 | 0.53 |
| | 4 | 0.00 | 0.07 | 0.14 | 0.21 | 0.28 | 0.35 | 0.42 | 0.49 | 0.63 | 0.63 | 0.71 |
| | 5 | 0.00 | 0.09 | 0.17 | 0.26 | 0.35 | 0.44 | 0.53 | 0.61 | 0.79 | 0.79 | 0.88 |
| | 6 | 0.00 | 0.10 | 0.21 | 0.31 | 0.42 | 0.52 | 0.63 | 0.74 | 0.95 | 0.95 | 1.06 |
| | 7 | 0.00 | 0.12 | 0.24 | 0.37 | 0.49 | 0.61 | 0.74 | 0.86 | 1.11 | 1.11 | 1.23 |
| | 8 | 0.00 | 0.14 | 0.28 | 0.42 | 0.56 | 0.70 | 0.84 | 0.98 | 1.27 | 1.27 | 1.41 |
| | 9 | 0.00 | 0.16 | 0.31 | 0.47 | 0.63 | 0.79 | 0.95 | 1.11 | 1.43 | 1.43 | 1.59 |
| | 10 | 0.00 | 0.17 | 0.35 | 0.52 | 0.70 | 0.87 | 1.05 | 1.23 | 1.58 | 1.58 | 1.76 |
| | 11 | 0.00 | 0.19 | 0.38 | 0.58 | 0.77 | 0.96 | 1.16 | 1.35 | 1.74 | 1.74 | 1.94 |
| | 12 | 0.00 | 0.21 | 0.42 | 0.63 | 0.84 | 1.05 | 1.26 | 1.47 | 1.90 | 1.90 | 2.12 |
| | 13 | 0.00 | 0.23 | 0.45 | 0.68 | 0.91 | 1.14 | 1.37 | 1.60 | 2.06 | 2.06 | 2.29 |
| | 14 | 0.00 | 0.24 | 0.49 | 0.73 | 0.98 | 1.22 | 1.47 | 1.72 | 2.22 | 2.22 | 2.47 |
| | 15 | 0.00 | 0.26 | 0.52 | 0.79 | 1.05 | 1.31 | 1.58 | 1.84 | 2.38 | 2.38 | 2.64 |

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